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Measurement of Vertical Turbulent Dispersion and Diffusion of Oil Droplets and Oiled Particles

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Engineering Hydraulics, Inc
Redmond, Washington
Project No. 438-005

Delft Hydraulics Laboratory
Delft, The Netherlands
Report No. Z 75-2

December 1987



Final Report

Measurement of Vertical Turbulent Dispersion and Diffusion
of Oil Droplets and Oiled Particles

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ABSTRACT

This study is part of a research program to develop mathematical models for the transport of spilt oil and the interaction of oil with suspended particulate matter (SPM) in the sea. The present laboratory experiments were conducted to provide the mathematical models with empirical data on oil dispersion and oil-SPM interaction.

Empirical relations and data were obtained for the following processes:

- a) break-up of surface oil films into droplets, and intrusion of droplets in the water column, due to breaking wave effects,
- b) break-up of submerged oil parcels (submerged leak) into droplets due to turbulence in the seawater,
- c) interaction between oil droplets and SPM.

The experiments were performed in three different laboratory facilities: (1) a grid column for experiments on submerged oil and oil-SPM interaction, (2) a small-scale wave flume for extensive series of experiments on dispersion of surface oil, and (3) a large-scale wave flume to relate the small-scale results to field conditions. (The large wave flume is almost full scale with waves up to 2 metres). The experiments were conducted in different conditions with respect to oil type and weathering state, SPM type, turbulence level and breaking wave energy, salinity and temperature.

The oil-SPM experiments led to mainly qualitative results on the influence of various parameters on the interaction process. The experiments on the break-up of surface oil films due to breaking waves led to the following quantitative relations:

- a) an empirical relation for the entrainment Q , as a function of the breaking wave energy, film thickness, oil type and temperature.
- b) a droplet size distribution as a function of these parameters.
- c) intrusion depth related to wave height and bore height.

The experiments on submerged oil in a turbulent ambience resulted in relations for the droplet size distribution in dependence of various parameters. The empirical relations can be used in mathematical models with given hydrodynamic conditions and breaking wave statistics.

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List of Symbols

		<u>units</u>
	°C	centigrade
	cSt	centistokes
	J	Joule
	g	gram
	kg	kilogram
	m	metre
	µm	micron
	N	Newton
	s	second
	‰	per thousand
a	wave amplitude	m
A	surface area	m ²
A _{grid}	grid oscillation amplitude	m
C, c ₁ , c ₂	constants in various equations	-
C _o	oil concentration	(ppm) g/m ³
C _s	silt concentration	(ppm) g/m ³
C _d	drag coefficient	-
c _w	phase velocity of wave	m/s
c _{bore}	bore propagation velocity of breaking wave	m/s
d _o	oil droplet size	µm , m
d _{min}	minimum oil droplet size	µm , m
d _{max}	maximum oil droplet size	µm , m
d ₅₀	averaged oil droplet size	µm , m
d _s	silt particle size	µm , m

$d_o(f)$	oil droplet size distribution	-
D_b	dissipated energy from breaking wave per unit width	J/m
D_{ba}	dissipated energy from breaking wave per unit area	J/m ²
E	energy	J
E_b	breaking wave energy dissipation rate per unit width	J/s m
E_{hj}	hydraulic jump energy dissipation rate per unit width	J/s m
e	energy dissipation rate per unit volume per unit time	J/s m ³
F	force	N
f	wave frequency	s ⁻¹
f_{grid}	grid oscillation frequency	s ⁻¹
F_{wc}	fraction of surface covered by white-caps per unit time	s ⁻¹
g	gravity constant	m/s ²
h	water depth	m
H	wave height	m
H_b	breaking wave height	m
h_{bore}	bore height	m
h_o	oil layer thickness	m
k	wave number	m ⁻¹
L	wave length	m
l_b	bore covered length	m
n	scaling factor	-
N	number of droplets	-
$N(d_o)$	number of oil droplets in an interval Δd around d_o , with $\Delta d \sim d_o$	-
$N_u(d_o)$	number of oil droplets in a unit size interval Δd around d_o	-

n_w	parameter defined in Equation (V.2)	-
OCC	organic carbon content (relative per weight)	%
o/s	oil-silt weight ratio	%
P	breaking wave energy flux per unit width	J/s m
PS	integrated power spectrum	m ² s
Q	mass of oil entrained per unit surface area per breaking event	kg/m ²
Q_r	mass of oil entrained per unit surface area per unit time	kg/m ² s
Q_{tot}	mass of entrained oil per breaking event	kg/m
S	salinity	‰
S_{cov}	fraction of surface covered by oil	-
t	time	s
t_{grid}	grid oscillation time	s
t_b	time of wave breaking	s
t_m	time of measurement after start of grid oscillation or after breaking wave event	s
t_s	characteristic time scale of breaking-wave turbulence	s
T	temperature	°C
T_w	wave period	s
t_s	characteristic time scale of breaking-wave turbulence (Eq. V.15)	s
u	flow velocity	m/s
u_c	cart velocity	m/s
U_w	wind speed	m/s
V	volume	m ³

$V(d_o)$	volume of dispersed oil droplets with droplet sizes in the interval $\frac{1}{2}d_o$ to d_o	m^3
$V_t(d_o)$	volume of dispersed oil droplets with droplet sizes smaller than d_o	m^3
V_{tot}	total volume of dispersed oil droplets	m^3
W	terminal velocity, fall velocity	m/s
x	horizontal length coordinate	m
z	vertical length coordinate	m
z_i	intrusion depth of oil droplets due to breaking wave	m
z_s	depth below the water surface	m
α	breaking wave constant ($\alpha = E_b/E_{hj}$)	-
η_K	Kolmogorov length scale	m
η	water level elevation	m
c	diffusion coefficient	m^2/s
c_z	coefficient for diffusion in vertical direction	m^2/s
ν_o	kinematic viscosity of oil	$(10^6 \text{ cSt}) m^2/s$
ν_w	kinematic viscosity of water	m^2/s
ω	angular velocity	rad/s
ρ_o	density of oil	kg/m^3
ρ_s	density of silt	kg/m^3
ρ_w	density of water	kg/m^3
$\Delta\rho$	density difference	kg/m^3
σ_o	oil surface tension	N/m
σ_w	water surface tension	N/m
σ_{ow}	oil-water interfacial tension	N/m

EXECUTIVE SUMMARY

Introduction

The purpose of the study on "Vertical Turbulent Dispersion of Oil Droplets and Oiled Particles" was to make available experimental laboratory measurements on the effects of turbulence on oil droplet size, vertical dispersion and diffusion rates for droplets and oiled particles, and the resulting oil distribution. The project was part of a series of studies to develop mathematical models for transport of spilt oil in the surf zone and for the interaction of oil and suspended particulate matter. The present laboratory experiments were designed to provide the mathematical models with empirical data.

The investigation was divided into the literature review, addressed in the Interim Report (Delvigne et al., 1986), and the experimental laboratory investigation reported in this document. The study has led to the preparation of a scientific paper, given in Appendix B.

The laboratory study dealt with the following dispersion processes:

- a) break-up of surface oil films into droplets and penetration into the water column due to breaking waves,
- b) break-up of oil parcels from a submerged leak into droplets due to turbulence in the water flow,
- c) diffusion of oil droplets,
- d) interaction between oil droplets and Suspended Particulate Matter (SPM).

The dispersion processes were investigated varying the following parameters:

- a) oil type and weathering state
- b) oil concentration and surface film thickness
- c) SPM type and concentration
- d) turbulence level
- e) water depth

f) water temperature.

The laboratory investigation was bound to include the translation of the empirical results to field situations. The laboratory-field translation was obtained and/or checked by specific experiments. The following three laboratory facilities were chosen for the performance of the experiments taking into account the measurement capabilities, the necessity of scaling and the eventual need of laboratory-field translation:

- a) grid column (4 m high, 0.3 wide). Turbulence was generated by an oscillating grid. The energy levels and structures of the important small-scale turbulent eddies are equal in the column and in field conditions.
- b) Oil Flume (15 m long, 0.5 m wide, 0.43 m water depth). Breaking waves with a height of 0.2 m were generated by a wave board. The waves were scaled to considerably smaller values than in field conditions.
- c) Delta Flume (200 m long, 5 m wide, 4.3 m water depth). Breaking waves were generated on (almost) field scale.

Comprehensive series of measurements were conducted in the relatively easily manageable grid column and Oil Flume, while a restricted program was performed in the large Delta Flume to derive scaling factors for the laboratory-field translation.

Effect of Turbulence on Oil Droplet Size

The mechanical action of breaking waves and turbulence in seawater causes spilt oil to break-up into small droplets and the droplets to diffuse in the water mass. The influence of different turbulence energy levels on the oil droplet size, d_o , was investigated by experiments in the grid column. The oscillating grid generated homogeneous turbulence in the column. The small-scale structures of the turbulence, responsible for the break-up of oil droplets (and also for the collisions of particles in the oil droplet - SPM interaction process), were similar and with equal energy levels in the column and in field conditions. The measurements of droplet size in the turbulent ambience in the grid column were conducted with unscaled field conditions of the relevant parameters. The following parameters were

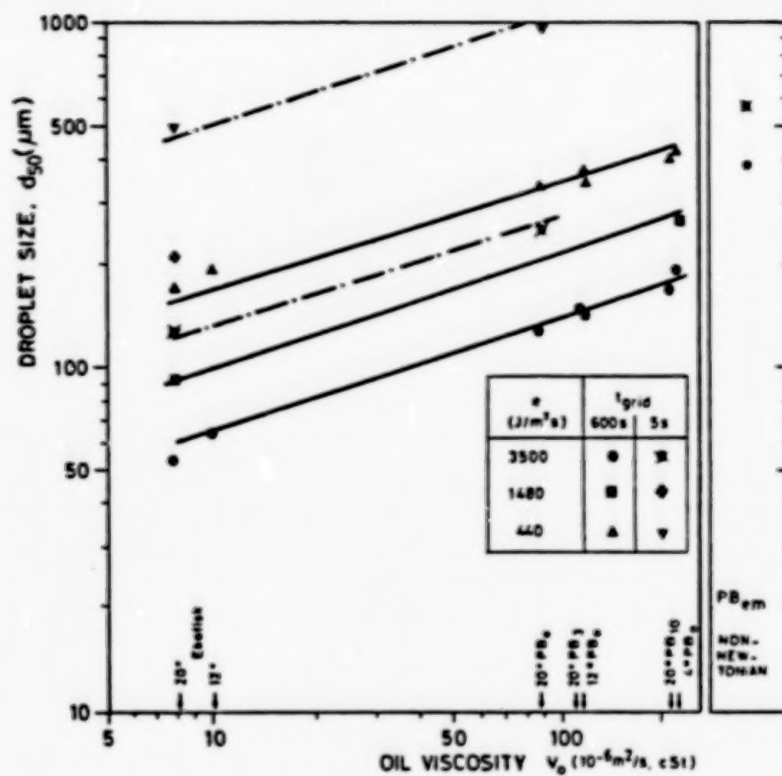
varied in the grid column experiments:

- a) oil type: Prudhoe Bay oil (PB) and Ekofisk oil (Eko) with relatively high and low viscosities respectively,
- b) oil weathering state: unweathered PB oil (PB_0), weathered oil by 3 day and 10 day evaporation (PB_3 , PB_{10}), and emulsified oil (PB_{em}),
- c) turbulence level: turbulence energy dissipation rate per unit volume, ϵ , from 0 to $3500 \text{ J/m}^3\text{s}$ (The high energy levels correspond with the energy dissipation in breaking wave bores in field conditions),
- d) turbulence duration: $t_{grid} = 5 \text{ s}$ for simulation of the short-duration turbulence of a breaking wave, and $t_{grid} = 600 \text{ s}$ to obtain a steady state droplet size distribution,
- e) temperature: $T = 4 \text{ to } 20^\circ\text{C}$,
- f) water salinity: from fresh water to seawater conditions,
- g) oil phase: surface oil film and submerged oil lumps.

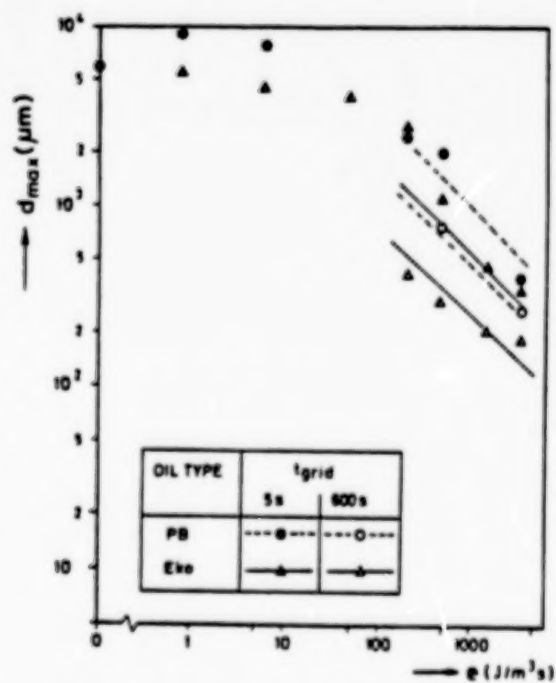
The droplet size distributions, $d_o(f)$, in these series of measurements were measured with a Laser-Beam Particle Sizer (LBPS). In the course of the study it appeared that in practice the measurable droplet size range was from about $50 \mu\text{m}$ until $2000 \mu\text{m}$. Smaller droplets were certainly present but were not measured with the LBPS. (Small droplets were measured by microscope in later series of experiments). The measurements with the LBPS were therefore used mainly to determine the influence of various parameters on the mean droplet size, d_{50} , and on the maximum droplet size, d_{max} .

A part of the experimental results is given in Figure ES.1. The d_{50} and d_{max} measurements are given as a function of the oil viscosity for different turbulent energies, oil types, weathering states and temperatures. The measurements led to the following conclusions:

- a) d_{50} and d_{max} depend on the oil viscosity, ν_o , according to the empirical equation:



a) Mean droplet size d_{50} versus oil viscosity with different turbulent energy levels ϵ , and turbulence duration t_{grid} .



b) Maximum droplet size d_{max} versus turbulence energy ϵ .

FIGURE ES.1 Measurements on break-up of submerged oil in turbulent ambience

$$d_{50}, d_{\max} \sim v_o^{0.34} \quad (\text{ES.1})$$

d_{50} and $d_{\max}$ depend on oil type, weathering state and temperature only as far as these parameters influence the viscosity v_o .

Equation (ES.1) is supported by measurements in the viscosity range $v_o = 8$ to $200 \cdot 10^{-6} \text{ m}^2/\text{s}$ (8 to 200 cSt) and cannot be applied to the data of high-viscous emulsified Prudhoe Bay oil where the viscosity shows a non-newtonian behaviour.

- b) d_{50} and $d_{\max}$ depend on the turbulence level according to:

$$d_{50}, d_{\max} \sim e^{-0.50} \quad (\text{ES.2})$$

Equation (ES.2) is valid in a high-turbulence ambience where additional break-up due to shear on the rising buoyant droplets is negligible.

- c) The droplet sizes depend on the turbulence duration t_{grid} . A steady-state droplet size distribution was obtained after $t_{\text{grid}} \geq 5$ minutes. Consequently, the droplet size distribution due to a short-duration breaking wave is not a steady-state distribution.
- d) The droplet sizes are independent of the water salinity.
- e) The droplet size distribution is independent of the initial oil phase, either consisting of a surface oil film, or submerged oil parcels.

Oil - SPM Interaction

Dispersed oil droplets may interact with suspended particulate matter (SPM) in the ocean. Laboratory experiments were conducted to investigate the following oil-SPM interaction phenomena:

- a) equilibrium time for the interaction,
- b) oil content of oiled particles,
- c) preference for specific oil droplet sizes in the interaction processes,
- d) oil composition in oiled particles,
- e) flocculation characteristics.

The experiments were performed in saline water conditions in the grid column, with two types of oil (Prudhoe Bay and Ekofisk), two weathering states (PB₀ and PB₃), two types of particulate matter (kaolinite without organic carbon content, and natural Waddensea particulate matter with organic carbon content OCC = 7 percent), and with varying turbulence energies and turbulence duration (one minute to three hours).

During the experiments, water samples were removed from the grid column and poured in separatory funnels. Separation took place in:

- a) phase I, buoyant matter, consisting mainly of oil (SPM-coated oil droplets),
- b) phase II, matter still in suspension after a stationary period of twenty hours,
- c) phase III, sedimented matter consisting mainly of silt (oiled sediment).

The three phases were analyzed for chemical composition by gas chromatography (GC). Moreover, samples were removed and collected in sample cells for microscopic observation in the fluorescence-microscope apparatus. This apparatus made use of a UV light source to distinguish the fluorescent oil droplets from the non-fluorescent SPM particles.

The following conclusions were drawn from visual microscopy:

- a) Oil-SPM interaction phenomena ranged from "oil droplets coated with SPM particles", to "oil droplets incorporated in SPM flocs". The buoyant, neutral or negatively-buoyant behaviour of an agglomerate depends on the oil-SPM ratio in the agglomerate.
- b) The oil in oiled sediment consisted apparently of discrete droplets. The droplets observed in negatively-buoyant agglomerates were always in the size range $1 \mu\text{m} < d_o < 60 \mu\text{m}$, where $1 \mu\text{m}$ was the limit of observation with the applied equipment. The size distribution of oil droplets in the agglomerates was not significantly variable in experiments with different oil types, SPM types and turbulence levels, and neither was the SPM coating of buoyant oil droplets.

GC analysis of the oiled sediment led to the following conclusions:

- c) A steady-state in the oil-SPM interaction experiments was obtained within 20 minutes with kaolinite SPM, but was not obtained within three hours (= maximum duration of the experiments) with Waddensea SPM.
- d) The oil content in the sediment was linearly proportional to the applied oil volume. The oil content was less in conditions with low concentrations of oil and SPM where, apparently, the low particle collision probability restricted the interaction.
- e) Increasing turbulence level led to increasing oil/silt (o/s) ratio in the sediment probably due to (1) increasing number of small oil droplets, (2) increasing collision probability, and/or (3) different flocculation behaviour.
- f) The ranking of oil for oil adsorption on silt depends on the type of silt. PB and Ekofisk were equally adsorbed by kaolinite, but Ekofisk was considerably better adsorbed by Waddensea silt.
- g) The weathered PB₃ oil was more adsorbed by SPM than the unweathered PB₀ oil.
- h) Oil adsorption by Waddensea silt was considerably more dependent on variables (e.g., type of oil, turbulence level) than the oil-kaolinite interaction.

The purpose of the oil-SPM interaction experiments was to obtain data on the oil-SPM agglomerates, in particular with respect to buoyancy and floc size. These parameters are of great influence on the vertical motion of oiled particles in a turbulent ambience and, ultimately, on the sedimentation on the sea floor. The fundamental grid column experiments were to be preceded by flume experiments with breaking waves. However, considerations on the collision probability in the laboratory facilities (due to turbulence), and in the sample cells (due to differential settling) determined that considerable oil-SPM interaction would take place in the sample cells. Moreover, emulsification of the surface oil during a flume experiment and other aspects of the present measurement procedures would hamper the determination of a relation between the measured interaction data and a well-defined set of parameters. The intention of conducting oil-SPM interaction experiments in a wave flume was therefore abandoned.

Oil Dispersion due to Breaking Waves

Performance of small-scale experiments

Experiments were performed in the small-scale "Oil Flume", 15 m long, 0.5 m wide, and with a water depth of 0.43 m. The experiments concerned the effect of breaking waves on a surface oil film. The following parameters were measured:

- a) dispersed oil mass relative to the mass of the surface oil slick (entrainment Q),
- b) droplet size distribution $d_o(f)$ of dispersed oil droplets,
- c) vertical intrusion of oil droplets in the water mass (z_i).

The flume was equipped with a programmed wave generator. Seven wave trains were selected, characterized by a specific wave height and energy dissipation of the (single) breaking wave.

Oil was poured onto the water surface in the test section of the flume resulting in an oil film with a thickness h_o ($h_o = 0.6$ mm in most experiments). The entire path of wave breaking was located in the area covered by the oil film. The intrusion depth of the oil droplets due to breaking wave turbulence was observed by taking photographs of the oil droplets (or dye initially sprayed in the water surface) shortly after the wave passage.

In a first series of experiments, the droplet size distribution was measured in-situ with the LBPS in the 50 μ m to 2000 μ m size range. In a second series of experiments, samples were withdrawn and $d_o(f)$ was determined by droplet counting from photographs and direct microscopic observation of droplets in the sample cell. The design of the fluorescence-microscope apparatus enabled routine measurements of small droplets down to $d_o = 3$ μ m. The LBPS in-situ measurements as well as the sampling took place at different depths below the water surface, and at different times t_m after the passage of the breaking wave. The horizontal locations of LBPS measurements were fixed, but the samplers for microscope observation

were moved by a carriage along the flume to enable sampling during traversing of the entire length of the oil droplet cloud. The latter method enabled the determination of the total amount of oil dispersed by a breaking event.

Experiments were performed with the following variables:

- a) oil type: Prudhoe Bay (PB) and Ekofisk oil,
- b) weathering state: PB_0 and PB_{10} ,
- c) seven breaking waves with different energy dissipation: the total energy dissipation and the energy dissipation rate per unit surface area were measured,
- d) temperature: $T = 2, 8$ and $15\text{ }^{\circ}\text{C}$,
- e) oil layer thickness $h_0 = 0.2, 0.6$ and 1.2 mm .

Performance of large-scale experiments

Some of the small-scale flume experiments were also performed in the large-scale "Delta Flume", with a length scaling factor of $n_l = 10$ compared to the Oil Flume. This means that the water depth was increased from 0.43 to 4.3 m, and the wave height, for example, from 0.2 to 2 m. In many respects, the experiments in the large flume can be considered as full-scale experiments.

The large flume was equipped with a wave generator similar to that in the small flume. The wave generators were steered by the same wave train signals, with an amplitude scaling of $n_a = 10$ and a wave period scaling $n_{Tw} = 10^{\frac{1}{2}}$.

The experiments were as similar as possible to the small-scale flume experiments. The same droplet sampling system was used for microscopic determination of the droplet size distribution. Other samples were removed for oil concentration measurements with infrared spectroscopy. The varied parameters were the type of oil (PB_0 and Ekofisk) and the breaking wave energy.

Results of the Oil Dispersion Experiments

The grid column oil break-up experiments, and the small-scale and large-scale flume experiments led to the following empirical relationships for the oil entrainment Q , droplet size distribution $d_o(f)$, and intrusion depth z_i , which were valid for the applied conditions.

The droplet size distributions in all experiments followed the relation:

$$N_u(d_o) \sim d_o^{-2.3} \quad (\text{ES.3})$$

where $N_u(d_o)$ = number of droplets in a unit droplet size interval Δd around d_o (e.g., interval $d_o - \frac{1}{2}\Delta d$ to $d_o + \frac{1}{2}\Delta d$).

This distribution is valid in all conditions for droplet sizes down to at least $d_o = 3 \mu\text{m}$ (limit of routine measurements). The largest droplet size, d_{max} (generally of the order of magnitude of $1000 \mu\text{m}$), depends on oil characteristics, turbulence level, and resurfacing and diffusion mechanisms.

Equation (ES.3) implies that the following equation is valid for the relative volume of dispersed oil as a function of the size classes:

$$V_t(d_o) = 1.45 V(d_o) \quad (\text{ES.4})$$

with $V(d_o)$ = volume of oil droplets in the size interval $0.5 d_o$ to $1.0 d_o$

$V_t(d_o)$ = volume of oil droplets smaller than d_o .

Equation (ES.4) indicates a rapid volume decrease for smaller droplets.

Breaking wave turbulence caused an oil droplet intrusion depth z_i according to the following empirical equations:

$$\begin{aligned} z_i &= 1.5 H_b \\ z_i &= 3.4 h_{\text{bore}} \end{aligned} \quad (\text{ES.5})$$

with H_b = wave height and h_{bore} = bore height of the breaking wave.

The number of droplets and the droplet size distribution are homogeneously distributed over the depth within z_1 as far as the smaller droplet size classes are concerned, while inhomogeneities arise for larger droplets due to resurfacing.

The entrainment Q (kg/m^2) is defined as the dispersed oil mass in the water column per unit surface area per breaking event. Q depends strongly on the time t_m after the passage of the breaking wave due to resurfacing of big droplets. Therefore, the following description of Q and droplet size distribution $d_o(f)$ is adopted:

- a) $d_o(f)$ is homogeneously distributed over the intrusion depth z_1 for small droplet size classes not (yet) disturbed by resurfacing of droplets.
- b) the relative $d_o(f)$ distribution for small size classes is given by Equation (ES.3). Initially, immediately after the breaking event, Equation (ES.3) is assumed to be valid up to infinitely large droplets.
- c) Absolute values of $N(d_o)$ in given circumstances are required for one or more small droplet size classes fulfilling the homogeneity condition described in paragraph a. Empirical data are presented in this study.
- d) the stability and vertical diffusion of the small oil droplets and the resurfacing of large droplets in the residual turbulence conditions of the ambient flow after the breaking wave must be calculated starting from the conditions described in paragraphs a,b,c.

The grid column simulated the break-up of submerged oil (submerged spill). In this case, $d_{\max}$ depends on the turbulence level in the ambient water. Measurements of $d_{\max}$ values are given in Equations (ES.1) and (ES.2) and shown in Figure (ES.1b), for different oil types (PB₀ and Ekofisk) and different turbulence levels.

The oil entrainment rate per droplet size class $Q_r(d_o)$, due to breaking waves, can be described empirically by:

$$Q_r(d_o) = C(o) D_{ba}^{0.57} S_{cov} F_{wc} d_o^{0.7} \Delta d \quad (\text{ES.6})$$

where

- $Q_r(d_o)$ = mass of entrained oil droplets in a size interval Δd around the droplet size d_o (interval $d_o - \frac{1}{2}\Delta d$ to $d_o + \frac{1}{2}\Delta d$), per unit surface area (m^2) and per unit time (s),
- D_{ba} = breaking wave energy dissipation per unit surface area in a breaking event,
- S_{cov} = fraction of (sea) surface covered by oil ($0 < S_{cov} \leq 1$),
- F_{wc} = fraction of surface covered by breaking waves ("white-caps") per unit time,
- $C(o)$ = proportionality constant, depending on oil type, weathering state and temperature.

Equation (ES.6), with the empirical D_{ba} exponent 0.57, was valid over a wide range of breaking waves in both the small-scale and large-scale experiments, where D_{ba} varied with a factor of 900.

Empirical values of $C(o)$ for various oil types are:

$$\begin{aligned} C(PB_0) &= 840 \\ C(PB_{10}) &= 510 \\ C(Ekofisk) &= 1800 \end{aligned} \tag{ES.7}$$

The values in Equation (ES.7) are valid if $Q_r(d_o)$ is expressed in kg/m^2s , D_{ba} in J/m^2 , F_{wc} in s^{-1} , and d_o and Δd in m.

The values of $C(o)$ in Equation (ES.7) were derived from experiments performed at a water temperature of about 13°C. The influence of the temperature on Q_r , as far as it could be derived from the experiments carried out in the range of 2°C to 15°C, could be expressed by using the viscosity ν_o as a characteristic parameter:

$$C(o) \sim \nu_o^{-1} \tag{ES.8}$$

The oil entrainment Q , due to breaking waves, appeared independent of the oil surface layer thickness h_o , within the applied values $h_o = 0.2$ to

1.2 mm. The maximum droplet size d_{max} can be considerable larger than h_o . No empirical data are available for very thin oil surface films where the total entrainment Q is restricted to the volume of the surface slick. It is suggested that one assume oil droplet dispersion according to the given empirical relations from the smallest size class until the size class where Q equals the surface slick volume. Actually, this principle can be applied for all film thicknesses. For large thicknesses, the large droplet sizes computed in this way resurface quickly.

The empirical relations and coefficients for dispersion of oil due to breaking waves and/or turbulent seawater conditions can be applied in mathematical models where the hydrodynamical conditions of the sea are known. The hydrodynamical conditions must include the statistics on breaking waves on the sea surface (probability of breaking, breaking wave energy dissipation), and the advection and diffusion characteristics, and turbulence energy level of the flow field.

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I. INTRODUCTION AND OBJECTIVES

The purpose of the study on "Vertical Turbulent Dispersion of Oil Droplets and Oiled Particles" was to make available experimental laboratory measurements on the effects of turbulence on oil droplet size, vertical dispersion and diffusion rates for droplets and oiled particles, and the resulting oil distribution. The project was part of a series of studies to develop mathematical models for transport of spilt oil in the surf zone and for the interaction of oil and suspended particulate matter. The present laboratory experiments were designed up to provide the mathematical models with empirical data.

The present investigation was divided into three tasks:

- Task A: Literature review, to collect, review and discuss the useful knowledge for adequate performance of the laboratory measurements. The literature review was reported in the Interim Report "Research on vertical turbulent dispersion of oil droplets and oiled particles, literature review". (Delvigne et al., 1986).
- Task B: Turbulence effects on oil droplet size. Laboratory investigation to determine the effects of turbulence on the oil droplet size as a function of the following variables:
 - a) oil type and weathering state,
 - b) level of turbulence,
 - c) water depth, and
 - d) water temperature.

The level of turbulence and water depth were related with ocean conditions from near-calm to storm-driven waves and currents in the near-shore and surf zone.

- Task C: Turbulence effects on vertical dispersion, diffusion and distribution. Laboratory investigation to determine the effects of turbulence on dispersion and diffusion of oil particles, on the interaction of oil with suspended particulate matter (SPM), and on the diffusion of oiled particles. The following variables were treated:

- a) oil type and weathering state,
- b) oil concentration and surface film thickness,
- c) SPM type and concentration,
- d) turbulence level,
- e) water depth, and
- f) water temperature.

The turbulence level and water depth were related with any given ocean conditions.

The laboratory investigation (Tasks B and C) is addressed in this report.

In other words, the laboratory experiments in the Tasks B and C dealt with the following processes:

- a) break-up of coherent oil surface films into oil droplets and penetration of the droplets in the water column due to the action of breaking waves,
- b) break-up of oil parcels from a submarine leak into oil droplets due to turbulence in the water flow,
- c) diffusion of oil droplets, and
- d) interaction between oil droplets and suspended particulate matter.

All these processes were studied relative to the aforementioned variables.

The laboratory investigation was bound to include the translation of the empirical results to field situations for those processes that were dependent on parameters scaled from field to laboratory dimensions. The laboratory - field translation was obtained and/or checked by special experiments.

It is evident that much attention must be paid to the turbulent energy levels and the turbulent structures in field conditions and in the laboratory facilities. Turbulence plays major roles in many processes to be studied:

- a) break-up of oil droplets due to turbulence-induced shear
- b) oil-SPM interaction and coagulation of oil droplets due to turbulence induced collisions between the particles
- c) turbulent diffusion of oil droplets and oiled particles

d) break-up of coherent surface oil layers by the turbulence of a breaking wave.

It is well-known that turbulence can be described in terms of eddies with different sizes. The scale of the largest eddies is of the order of the dimensions of the water system (e.g., water depth). The energy in the energy-containing large eddies is transferred via smaller eddies (eddy cascading) to the smallest size classes where the energy is dissipated ultimately into heat under the influence of viscosity. (Batchelor, 1953). The smallest eddies are in the order of the Kolmogorov dissipation length η_k given by:

$$\eta_k = \left(\frac{\nu_w^3 \rho_w}{\epsilon} \right)^{1/4} \quad (1.1)$$

where ν_w = kinematic viscosity of water

ρ_w = density of water

ϵ = energy dissipation rate per unit volume

η_k is usually in the millimetre range.

The transport of turbulent energy via the eddy cascade, and Equation (1.1) implies similar small-scale eddy structures in different water systems if the energy dissipation rates ϵ are equal.

Particle collisions and break-up of oil droplets (and SPM flocs) are due to Brownian motions and differential settling (collisions), shear due to fall velocity and rise velocity (break-up), and shear due to velocity gradients caused by turbulence. The small size of the droplets and particles considered imply that the high velocity gradients (over a short distance) induced by the small eddies give the dominant contribution of the turbulence to the collision and break-up probabilities. This is shown by Camp and Stein's (1943) relationship for the collision frequency in turbulent flows which indicates that the frequency is proportional to $\epsilon^{1/2}$ as far as the turbulence is concerned, and as discussed before, the value of ϵ gives an indication of the small-scale eddies only in the turbulent structure.

The turbulent diffusion of oil droplets and SPM particles is mainly caused

by the largest eddies in the system because these eddies transport the particles over the greatest (and irregular) distances. The break-up of coherent surface oil layers and the intrusion of the oil parcels in the water column by breaking waves is a complex of processes where probably all eddy size classes in the breaking waves play important roles.

Whether or not the small-scale eddies, the large-scale eddies or the breaking waves must be scaled from field to laboratory values is important to the relevant processes to be studied.

Accordingly, it was important to keep parameters on field conditions as much as possible in order to reduce the translation from laboratory to field conditions. It appeared possible to reproduce the following parameters under similar conditions in the ocean and in the laboratory facilities:

- a) oil type,
- b) oil weathering state,
- c) thickness of oil surface film,
- d) SPM composition and particle sizes,
- e) water temperature,
- f) water salinity, and
- g) energy level of small-scale turbulent eddies (this parameter could be varied using field values in two of the three laboratory facilities used).

On the other hand, the following parameters must be scaled to laboratory values:

- a) water depth,
- b) breaking waves: scaling of wave height, wave period and energy dissipation (the scaling of the energy dissipation leads to a reduction of the energy level of the small-scale turbulent eddies),
- c) large-scale turbulent eddies.

The following three laboratory facilities were chosen for the performance of the experiments, taking into account the measurement capabilities, the necessity of scaling and the need of translation of the results to field

conditions:

a) Grid column.

Turbulence was generated in a 4 m high and 0.3 m wide cylindrical column by means of an oscillating grid. It was possible to keep the energy level of the small-scale turbulent eddies in the column at values equal to those in field conditions, including the high energy level due to breaking waves in the field.

The Task B experiments on the turbulence effects on the oil droplet size distribution were performed in the grid column; the experiments are described in Section III. A series of oil droplet - SPM interaction experiments (part of Task B) was also performed in the column, and is described in Section IV. All important parameters could be kept at field values in the experiments carried out in the column.

b) Small wave flume ("Oil Flume").

A small wave flume was used for most experiments on the effect of breaking waves on surface oil layers. The flume was 15 m long, 0.5 m wide, and had a water depth of 0.43 m. The wave heights of the breaking waves were of the order of magnitude of 0.2 m. The water depth and breaking wave parameters were scaled to considerably smaller values as compared with field conditions, including the energy level of the small-scale turbulent eddies due to breaking waves.

Experimental data were obtained on the break-up of coherent surface oil films, the intrusion of oil into the water column, and the break-up of oil parcels into small oil droplets, due to the breaking-wave turbulence. The experiments are reported in Section V.

c) Large wave flume ("Delta Flume").

A limited number of experiments were performed in a large wave flume to investigate oil dispersion at field scale or almost field scale, and to derive the translation relations for the extensive series of experiments in the small wave flume to field conditions.

The flume was 200 m long, 5 m wide and had a water depth of 4.3 m. The

wave heights of the breaking waves were of the order of 2 m. In many respects, the Delta Flume experiments could be considered as field experiments. The experiments are reported in Section VI.

The experiments in the grid column, small wave flume and large wave flume were conducted with partly different conditions, scaling factors and parameter values. The integration of the experimental results, described in Section VII, led to empirical equations for the following phenomena:

- droplets size distribution for oil in turbulent ambience, $d_o(f)$,
- entrainment of surface oil due to breaking waves, Q , and
- intrusion depth of oil due to breaking waves, z_i .

The empirical equations for $d_o(f)$, Q and z_i include the dependence on the type of oil, oil weathering state, oil film thickness, energy of breaking wave, and water temperature.

II. SUMMARY OF CURRENT KNOWLEDGE ON OIL DISPERSION

A literature review of current knowledge on oil dispersion, diffusion and oil-SPM interaction was reported as part of the present investigation in the Interim Report (Delvigne et al., 1986). The executive summary of the interim report is given in Section II.1, while Section II.2 gives an update of the current knowledge.

II.1 Executive Summary of the Interim Report on Vertical Turbulent Dispersion of Oil Droplets and Oiled Particles (Literature Review)

Topics considered in the Interim Report were selected with respect to their usefulness for the performance of laboratory measurements on vertical turbulent dispersion of oil droplets and oiled particles:

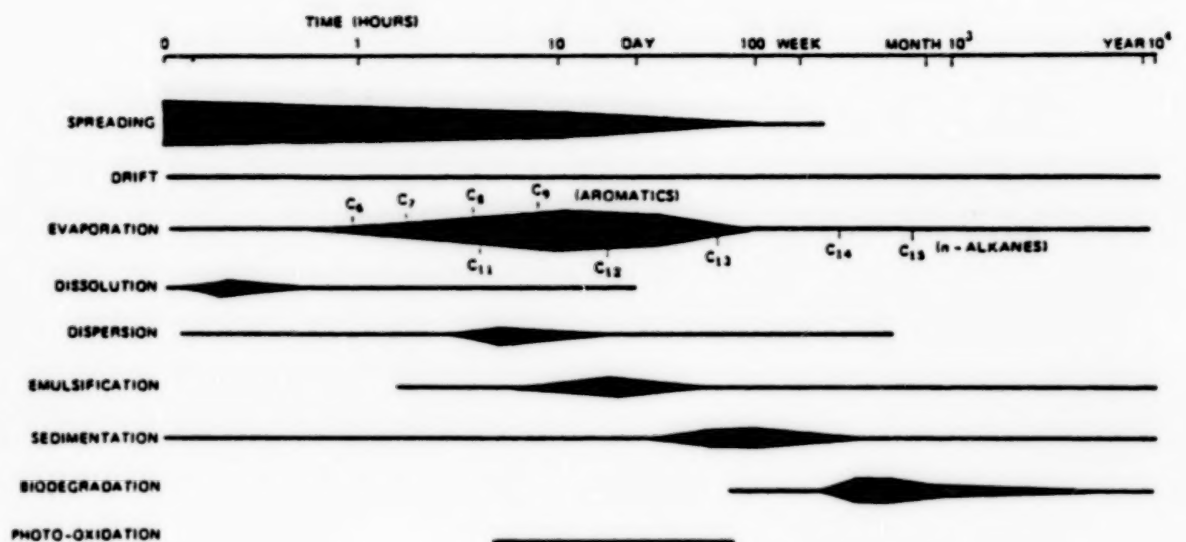
Oil properties

The overall physical oil properties (e.g., density, viscosity, surface tension) depend on the chemical composition. The rate constants of many processes dealing with oil vary for different oil components. These fractionation processes (e.g., evaporation, dissolution, photo-oxidation, biodegradation, spontaneous dispersion and oil - SPM interaction) change the composition of oil in the different liquid phases: surface oil, dispersed oil, dissolved oil and oil adsorbed by SPM. Therefore, determination of the chemical composition of oil in various phases is important in experiments on oil processes.

The physical properties of any type of oil depend on the temperature and the weathering state of the oil. The correlations of these properties with the temperature and the volume fraction evaporated are given in the Interim Report.

Fate of oil

Oil in the sea is subject to many processes, given in Figure II.1 together



The line length indicates the probable timespan of any process. The line width indicates the relative magnitude of the process through time and in relation to other contemporary processes.

FIGURE II.1 Processes versus time elapsed since the spill
(Wheeler, 1978)

with the probable timespan of the process. Evaporation, dissolution, emulsification and dispersion have been discussed because these processes may influence the behaviour of oil in the water column, and the oil - SPM interaction.

Theory on dispersion

The dispersion process of a coherent oil film into droplets is distinguished in spontaneous dispersion and mechanical dispersion. Spontaneous dispersion is a chemical-physical fractionation process leading to a stable situation with small oil droplets, called micelles, with droplet size $d_o \leq 1 \mu m$.

Mechanical dispersion (dispersion by agitation) forces the consideration of many processes dealing with the sea state. Primary attention is paid to the following phenomena:

- formation of oil droplets from a coherent slick and the initial intrusion of the droplets in the water column due to (breaking) waves
- advective and diffusive transport of oil droplets by currents and turbulence.
- coagulation and splitting of oil droplets.

It is evident that the turbulence in the water phase is important for all these phenomena. (Aravamudan et al. 1982) have compiled the results of mechanical dispersion studies (Milgram et al. 1978, Ray 1977, Lin et al. 1978) into mathematical models, with breaking waves being the mechanism for dispersion. Using the Weber number approach, they calculated the theoretical maximum oil droplet size and the critical size below which no splitting will occur, but knowledge of breaking waves is limited. The time scale of the droplet splitting process is unknown.

The effect of turbulent diffusion and terminal velocity W on the vertical transport of oil droplets is given by:

$$\frac{\partial C_o}{\partial t} = \frac{\partial}{\partial z} \left[\epsilon_z(z) \frac{\partial C_o}{\partial z} \right] + W \frac{\partial C_o}{\partial z} \quad (2.1)$$

where C_o = oil concentration
 c_z = vertical diffusion coefficient
 W = terminal velocity of the oil droplets
 z = vertical length coordinate
 t = time

Vertical transport of oil droplets by turbulent diffusion was calculated by Johansen and Audunson (1982), with estimates of sea-state dependent diffusion coefficients, and laboratory measurements on the initial intrusion of droplets in the water column by breaking waves.

Measurements on dispersion

Field data on dispersed oil droplet size distributions are very scarce. Stable oil dispersions with a mean droplet size around 20 to 40 μm were found under vigorous wave and current action (Forrester 1971, Berridge et al. 1968).

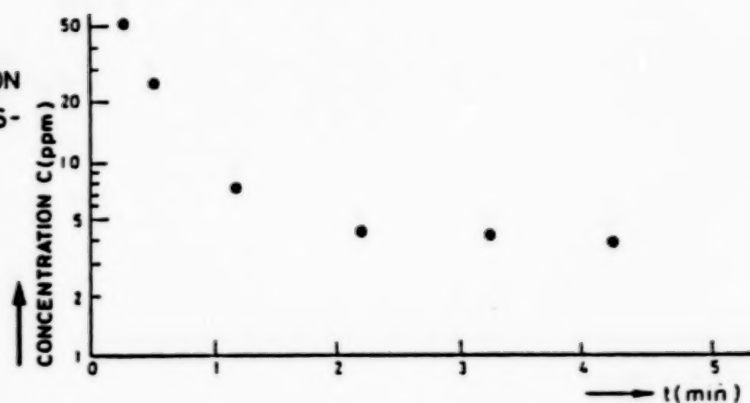
Delvigne (1984, 1985) measured the droplet size distribution of oil dispersed by breaking waves in a laboratory flume. Typical graphs of oil concentration and droplet size distribution over time in the water column are shown in Figure II.2. The declining concentration and mean droplet size over time was due to resurfacing of the bigger oil droplets.

Field data on oil concentration in the water column range from 500 ppm in the nearshore zone for large actual spills, to 0.01 ppm for test spills.

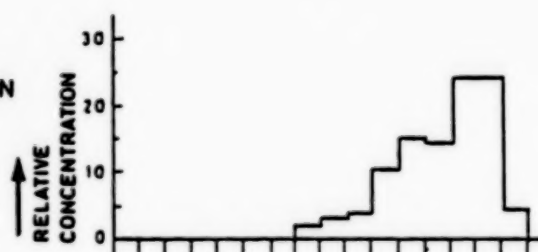
SPM properties

In most cases, SPM is a mixture of inorganic and organic particles. Small cohesive inorganic particles are usually coated with a few percent of organic matter. The organic carbon content is an important parameter because the adsorption of oil is proportional to the percentage of carbon content according to experiments by several authors.

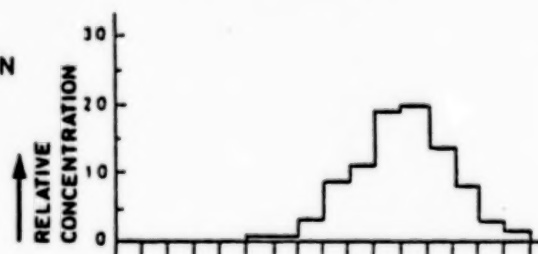
a) DISPERSED OIL CONCENTRATION
VERSUS t_m (= TIME AFTER PASSING OF BREAKING WAVE)



b) DROPLET SIZE DISTRIBUTION
AT $t_m = 10$ s



c) DROPLET SIZE DISTRIBUTION
AT $t_m = 70$ s



d) DROPLET SIZE DISTRIBUTION
AT $t_m = 190$ s

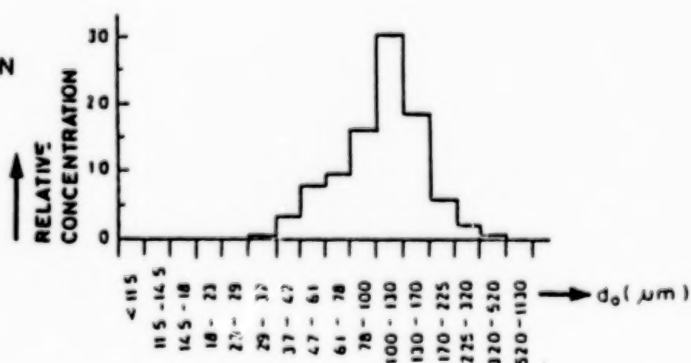


FIGURE II.2 Dispersion of no.2 fuel oil by breaking wave in a laboratory flume (Delvigne 1984)

The vertical distribution of SPM within a flow depends on the relative magnitude of turbulence (diffusion) and fall velocity. The fall velocity is not a constant parameter but changes as the flocculation process proceeds. No reliable methods exist to predict the size, density and fall velocity of SPM and resulting flocs in a flow.

Oil - SPM interaction

Oil adsorption is generally believed to take place mainly by adsorption of thin oil films onto clay particles which are subsequently flocculated, rather than by adsorption of discrete oil droplets. (This study appears to prove to the contrary).

Many fundamental phenomena are similar for the flocculation process of SPM, the coagulation of oil droplets, and the aggregation of oil droplets and SPM. These phenomena are:

- a) stabilization of dispersed droplets and SPM by electric surface charges,
- b) destabilization by reduction of the surface charges, due to adsorption of electrolytes (salt) from the seawater,
- c) collisions between particles due to Brownian motion, turbulence or differential settling.

Oil film adsorption onto SPM results in partitioning of the oil. Many investigators have searched for correlations between the adsorption rate and various parameters, with the following results:

- a) distinct negative correlation was found between the adsorption rate and the solubility of the oil component.
- b) increasing water temperature results in a decrease in adsorption due to the increased water solubility.
- c) solubilization of oil components by dissolved organic matter in seawater reduces adsorption.
- d) oil adsorption depends on the SPM composition, particle size and the organic carbon content of the particulate matter.

- e) the salinity of the water influences the oil droplet - SPM aggregation and the oil film adsorption.

Oil sedimentation models in the literature are based on scarce empirical information and oversimplification of various processes. Reliable quantitative results cannot be expected.

Ocean conditions

The behaviour and interaction processes of spilt oil and SPM in the ocean are influenced by many parameters, e.g., temperature (influence on oil viscosity and solubility of oil components) and salinity (destabilization of oil - SPM agglomerates due to adsorption of electrolytes). Temperature and salinity conditions in the ocean are discussed. The most important ocean condition parameters for the dispersion, diffusion and interaction process of oil and SPM are:

- a) the turbulent energy dissipation rate per unit volume, ϵ
- b) the vertical diffusion coefficient, ϵ_z .

These parameters characterize the turbulence conditions due to currents, wind and (breaking) waves. The parameters ϵ and ϵ_z are estimated in the following ocean zones:

- a) surf zone, with breaking waves as the dominating mechanism. The energy dissipation is assumed to take place over the full water column.
- b) coastal zone, where turbulence due to "whitecapping" and turbulence induced by bottom friction are of the same order of magnitude. Different conditions exist near the bed, at middepth and near the water surface.
- c) deep-water zone, where turbulence due to whitecapping is the dominating mechanism.

Simulation of ocean conditions in laboratory models

The modelling of the behaviour and interaction of oil and SPM requires the application of the same materials in the laboratory as in the ocean.

Therefore, the turbulence modeling must fulfil the following requirements:

- a) appropriate scaling of large-scale eddies for adequate simulation of diffusion processes
- b) appropriate scaling of small-scale eddies for adequate simulation of splitting and interaction processes of droplets and particles.

However, the impossibility of appropriate scaling of both eddy ranges at the same time forces the performance of different laboratory experiments, each with adequate simulation of a limited number of processes.

II.2 Supplement to the Interim Report

The following recent publications contribute significantly to the knowledge of oil dispersion:

Elliot (1986) prepared a numerical model and conducted field experiments on the spreading of oil within a few hours after the release of a slick. The emphasis on this time period is justified by the fact that weathering of oil is particularly important during the first few hours. The phenomena described in the three-dimensional model are represented schematically in Figure II.3. Much attention was paid to the effect of shear from tidal streams, wind and waves on the dispersion and diffusion of oil. A patch of oil was modelled as a droplet distribution in the size range from $d_0 = 10$ to $500 \mu\text{m}$, with the number of droplets uniformly distributed over the size range. A random walk technique was used to follow the motion of individual oil droplets. The droplets move around within the total velocity field as a result of diffusion and buoyancy. Horizontal and vertical diffusion coefficients near the upper layer were estimated from field dye experiments. There is evidence that the model is valid in the upper layer where the mixing is dominated by wind and waves.

Thorpe (1984 a, b) investigated the turbulent transport at the surface. The turbulence in the near-surface layer includes turbulence generated by breaking waves, Langmuir circulation, etcetera. The vertical diffusion coefficient ϵ_z in the surface layer was determined from field measurements on the size distribution of air bubbles as a function of depth, where the

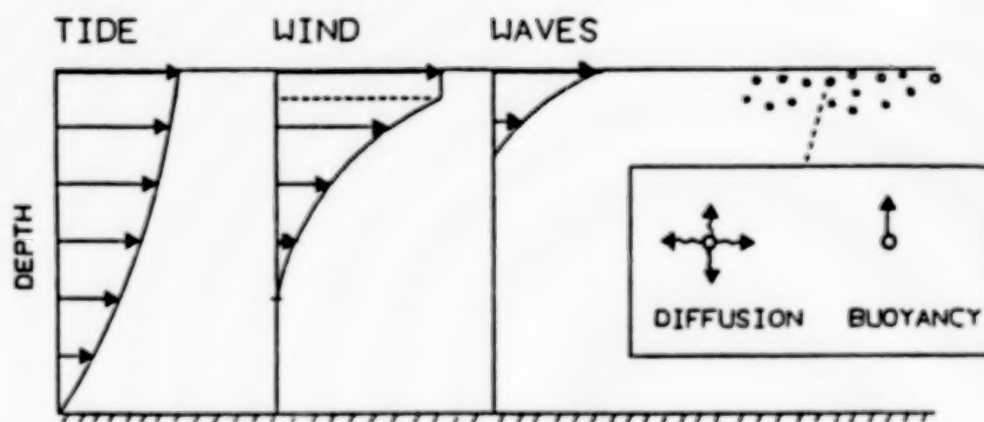


FIGURE II.3 Schematic representation of the mechanisms included in Elliot's (1986) model

air bubbles were generated by breaking waves. Results are given in Figure II.4, showing the variation of ϵ_z at 1.5 m depth with the wind velocity U_w . (The open circles refer to a coastal area, the solid circles to a lake. The cross represents the error estimates of the data).

As regards the break-up of oil films by breaking waves and the subsequent diffusion of oil droplets, it is very important to know the statistics of breaking waves in given conditions (probability of breaking, energy dissipation during breaking), and the turbulence and diffusion in the upper layer in the sea. This was already discussed in the Interim Report (1986). Bondeur and Sharkov (1982) analyzed aerial photographs of the sea surface with areas of foam due to breaking waves (whitecaps). The dependence of the average areas covered by breaking waves on the wind speed is defined for the wind speed range from 2 to 10.5 m/s. The generation of breaking waves exhibits a wind velocity threshold of 4 to 5 m/s. Other recent contributions on breaking wave statistics are by Glazman (1985), Phillips (1985) and Huang et al. (1986). Important contributions in the field of turbulence in the surface layer of the sea, under breaking and non-breaking waves, were presented at the Sendai (Japan) Symposium on Wave Breaking, Turbulent mixing and Radio Probing of the Ocean Surface, by Mitsuyasu and Kusaba (1985), Terray and Bliven (1985), Wang and Wu (1985), Okuda (1985), Melville et al. (1985), Hattori et al. (1985) and Jones (1985), all concerning laboratory measurements.

Bouwmeester and Wallace (1986) conducted laboratory experiments on oil dispersion in a 17 m long wind-wave flume. The wind-wave conditions were such that waves began to break and continued to break intermittently in the measuring section. Oil was released at the upwind end, resulting in oil film thicknesses of 0.3 and 0.8 mm. Oil concentrations and oil droplet size distributions were measured below the water surface. The range of droplets measured was between 12 and 2000 μm , while the number of droplets decreased exponentially with increasing droplet size. Examples are given in Figure II.5. The droplet size distribution at the surface level was approximated by:

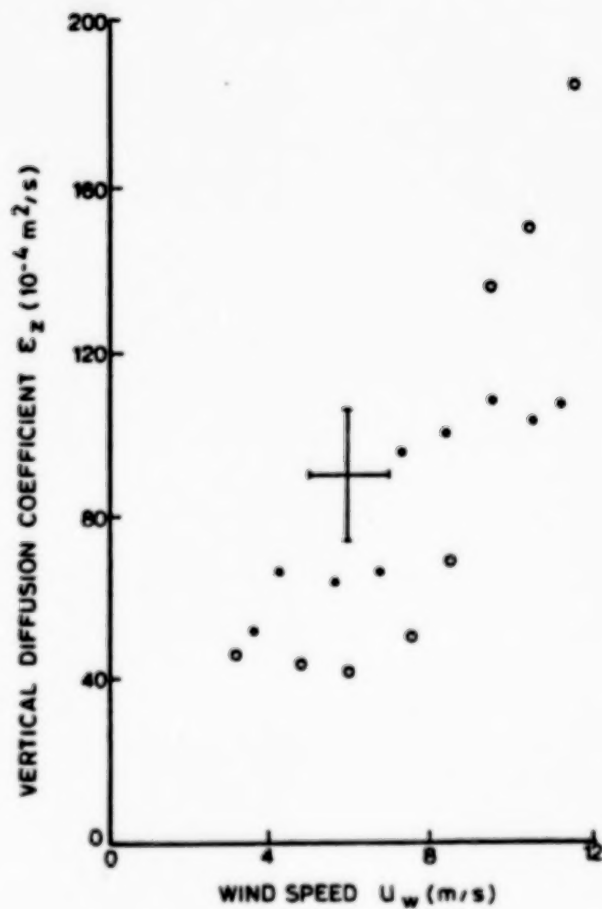
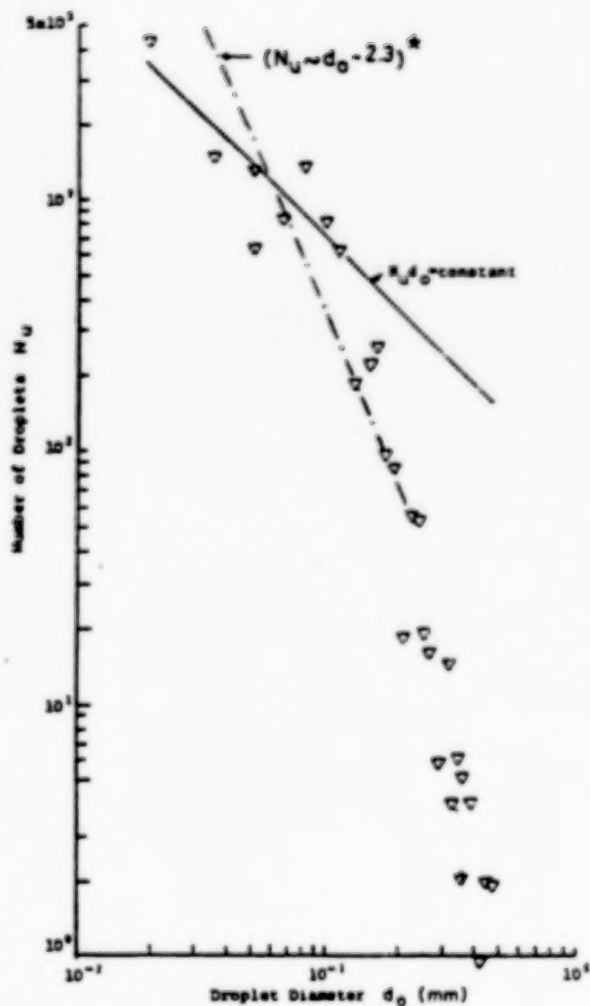
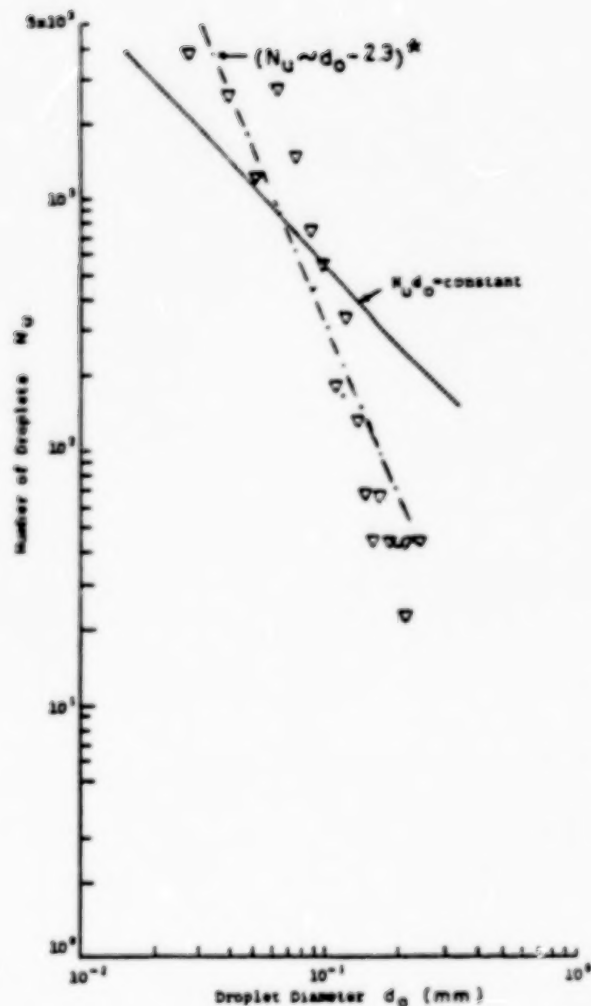


FIGURE II.4 Vertical diffusion coefficient at 1.5 m depth versus wind speed. (Thorpe, 1984)



a) Condition II,
oil release 0.11 l/s



b) condition III,
oil release 0.35 l/s

* $N_u \sim d_o^{-2.3}$ curves were incorporated according to the results of the present study

FIGURE II.5 Measured droplet size distributions of dispersed oil in wind-wave flume experiments. (Bouwmeester and Wallace, 1986)

$$N_u(d_o) \cdot d_o = \text{constant}$$

where $N_u(d_o)$ = number of droplets in a droplet size interval, and d_o is the droplet size at the midpoint of the respective interval. The dispersed oil concentration was independent of the oil film thickness, but more large droplets were formed with the larger film thickness.

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III. EFFECTS OF TURBULENCE ON OIL DROPLET SIZE

III.1 Introduction

The mechanical action of breaking waves and turbulence in the seawater causes spilt oil to break up into small droplets and the droplets to diffuse into the water column. The droplet size distribution of the dispersed oil is an important parameter because it affects:

- a) the stability of the dispersion (oil-in-water emulsion) and consequently, the concentration of oil in the water column,
- b) the uptake of oil by marine life, e.g., the ingestion of oil droplets by zooplankton,
- c) the adsorption of oil by suspended particulate matter and the subsequent sedimentation of oil on the sea floor.

It is very important to remember that only the small turbulent eddies in the turbulence structure are responsible for the break-up of oil into small droplets (see Section I).

Fundamental effects of turbulence on the oil droplet size distribution in various circumstances were investigated by experiments in a laboratory grid column. (The grid column is described in Appendix A.1.1). The oscillating grid generated homogeneous turbulence in the column. The small-scale turbulence structure in the column is similar to ocean conditions if the turbulent energy dissipation rates per unit volume are equal. The energy dissipation rate per unit volume e in the column could be varied in the range $e = 0$ to $3.5 \times 10^3 \text{ J/s m}^3$, while values of e in field conditions are in the following ranges:

deep-sea	$e = 10^{-4} - 10^{-2} \text{ J/s m}^3$
estuary	$e = 10^{-1} - 10^0 \text{ J/s m}^3$
surface layer	$e = 10^0 - 10^1 \text{ J/s m}^3$
breaking wave	$e = 10^3 - 10^4 \text{ J/s m}^3$

(The field data were obtained from empirical equations given in the Interim Report, Sections 7.5 to 7.8, and from field measurements. See, for instance, the deep sea energy dissipation measurements of Crawford and

Osborn, 1981).

The measurements of oil droplet size in turbulent conditions could be performed in the grid column with field values of essential parameters, consequently scaling to a laboratory scale was not necessary.

The large depth of the column, 4 m, enabled a long period of measurement in certain turbulent conditions before differential rising of oil droplets distorted the droplet size distributions.

The droplet size distributions were experimentally determined in the grid column as a function of the following parameters:

- a) turbulence energy level and turbulence duration
- b) oil type
- c) oil weathering state (weathering by evaporation and emulsification)
- d) oil concentration
- e) subsurface and surface introduction of oil in the water
- f) temperature of the water
- g) salinity of the water

III.2 Experimental Set-up

The measurements were performed in the grid column shown in Figure III.1.

Application of submerged oil in the column was performed by introduction of large oil droplets with diameter $d_o = 10$ mm by a bottom inlet during a certain time (Figure A.2). The oil input was stopped and the turbulence grid switched on when the droplets were distributed homogeneously as possible in the column. The size of the initial oil droplets was chosen large enough to guarantee the break-up of the droplets in any turbulence condition in the flume. Droplets of 10 mm appeared unstable even in non-turbulent condition: break-up will occur due to the drag force on the rising droplet.

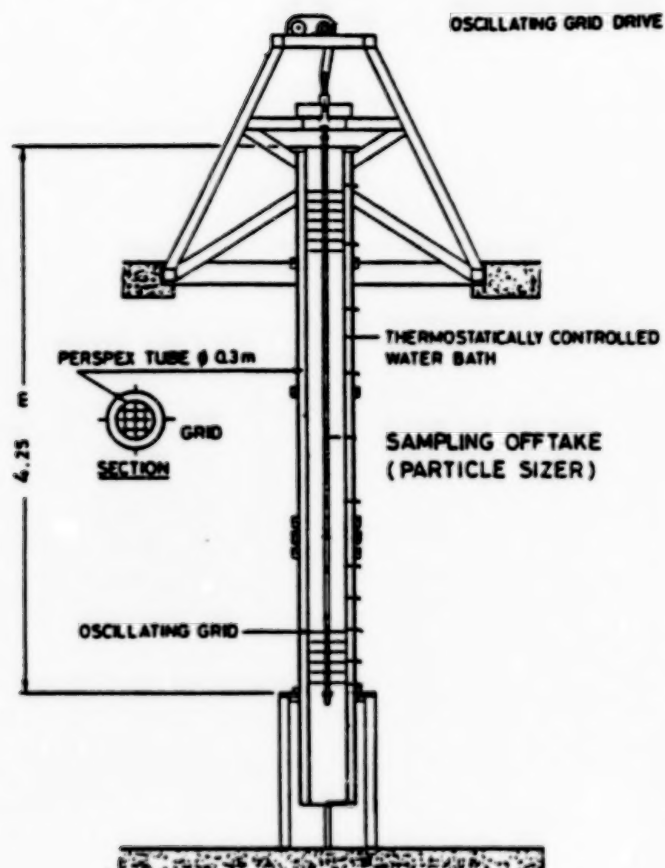
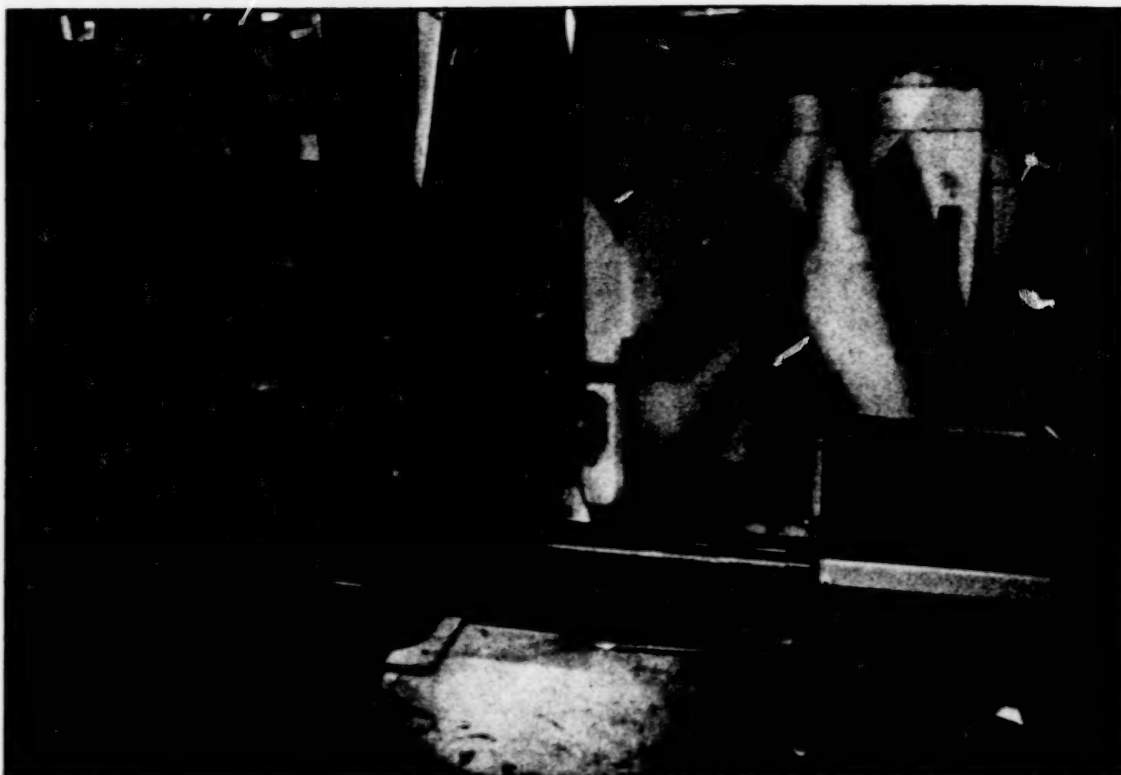


FIGURE III. 1 Grid column

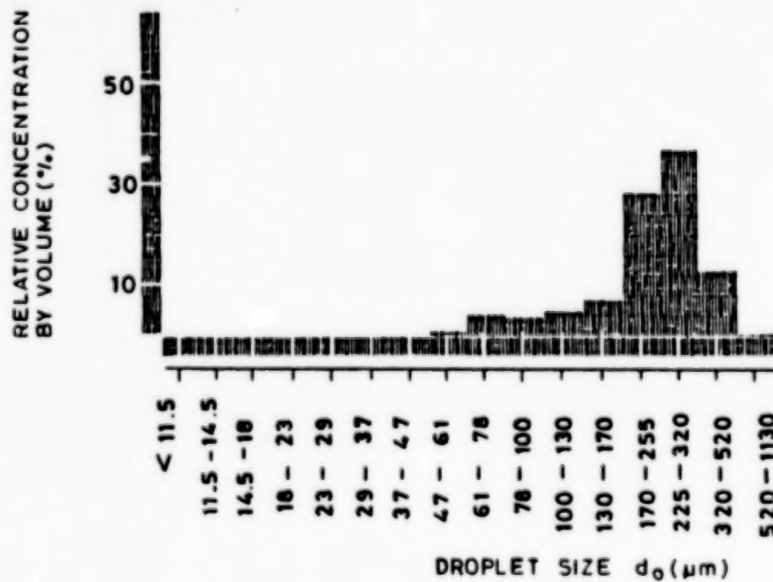
In a few cases, the oil was poured as a surface film to check for differences in droplet size distribution between surface oil films and subsurface oil parcels. The oil was applied to the water surface and spread until a film thickness of $h_o = 0.25$ mm was attained. The water level above the grid was chosen large enough to avoid intersection of the water surface by the grid and to avoid "breaking waves" generated by the grid. The water level is low enough to generate oil entrainment from the surface into the column due to turbulence from the oscillating grid.

The droplet size distribution was measured by a Laser-Beam Particle Sizer (LBPS) by continuous flow-through water sampling. (See Figure III.2a, the LBPS is described in Appendix A.2.1). A typical data example is given in Figure III.2b. The data were provided by the LBPS with the optical system for droplet size measurement in the size range $d_o = 11.5$ to 1130 μm . The division of the total range in subranges is shown in the figure along the abscissa of the graph. The ordinate shows the relative concentration of droplets in a subrange by volume, where 100 % represents the total volume of oil droplets in the entire measurable range from 11.5 to 1130 μm . The minimum detectable oil concentration in a subrange is 0.1 %. In the course of the study it became apparent that this minimum concentration is a serious limitation for measurement of the complete droplet size distribution including the small droplets (Appendix A.2.1). A subsequently applied droplet size measurement technique with microscopic observation of droplets (Appendix A.2.2) showed a considerable increase in number of droplets $N(d_o)$ with decreasing droplet size d_o at least down to $d_o = 5$ μm . However, the volume of oil in a subrange declined considerably. Therefore it is emphasized that the minimum droplet size observed with the LBPS indicates the smallest droplet size $d_{\min}$ with $V(d_{\min}) > 10^{-3} V_{\text{tot}}$, where $V(d_{\min})$ = volume of oil in the size range around $d_{\min}$, and V_{tot} the volume of oil in the entire range of measurement.

Almost all column experiments were recorded on video tape through a 0.2×0.2 m "window" in the wall of the column. A video picture is shown in Figure III-3. The video recording was especially important for experimental conditions where droplets occurred with $d_o \geq 1000$ μm that



a) LBPS apparatus



b) Example of LBPS data

FIGURE III. 2 Laser-Beam Particle Sizer (LPBS) in grid column experiments

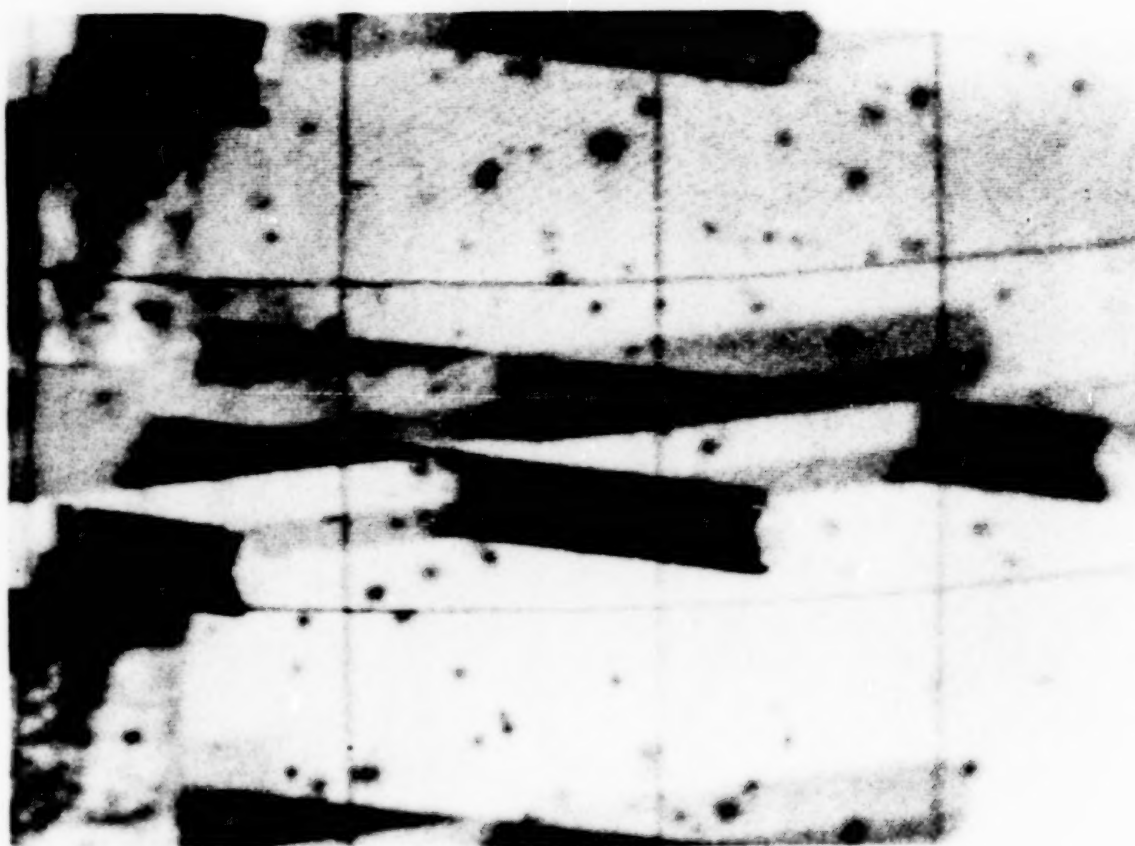


FIGURE III. 3 Video registration of large oil droplets in the grid column

could not be detected with the LBPS. These droplets sizes were determined from video recordings by observation of the terminal velocities. Video measurement of large droplet sizes is only possible with a switched-off grid after an oscillation period. Measurements with the LBPS were performed during and after oscillation of the grid.

The video measurements of d_0 made use of the terminal velocity curves shown in Figure III.4. These curves (for Prudhoe Bay crude and Ekofisk crude, at 20°C) were constructed from calculation with Stokes' equation for small droplets, $d_0 \leq 150 \mu\text{m}$, from video observation for very large droplets, $d_0 \geq 1500 \mu\text{m}$ where droplet size and terminal velocities can be observed accurately, and from interpolation for droplets with $150 \mu\text{m} < d_0 < 1500 \mu\text{m}$.

III.3 Presentation of Measurements

Oil droplet size distributions were measured in the grid column as a function of the following parameters:

- a) oil type:
 - PB = Prudhoe Bay crude (Alaska)
 - Eko = Ekofisk crude (North Sea)
- b) oil weathering state:
 - PB₀ = Prudhoe Bay crude, unweathered
 - PB₃, PB₁₀ = Prudhoe Bay crude, weathered by 3 day and 10 day evaporation respectively*
 - PB_{em} = Prudhoe Bay crude - water emulsion, with oil-water ratio 1:3
 - Eko = Ekofisk crude, unweathered
- c) grid oscillation, different frequencies lead to turbulent energy dissipation rate, ϵ , in the range $\epsilon = 0$ to 3500 J/s m^3 .
- d) duration of grid oscillation t_{grid} :
 - $t_{\text{grid}} = 5 \text{ s}$ (simulation of the turbulence field from a single breaking wave)
 - $t_{\text{grid}} = 600 \text{ s}$ (simulation of steady state turbulence)

* The meaning of the 3 and 10 day laboratory weathering with respect to field weathering is described in Appendix A.3.2.

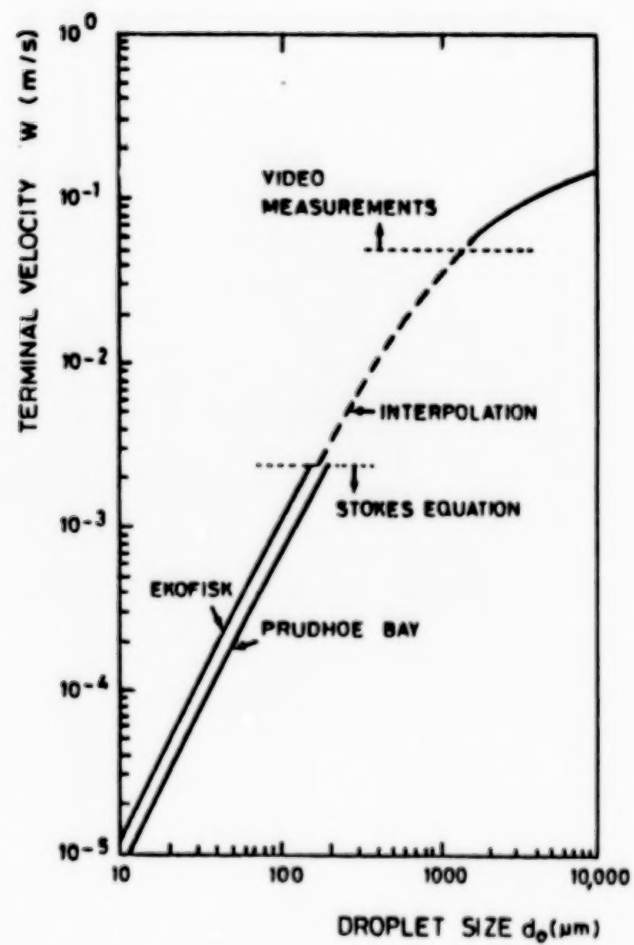


FIGURE III.4 Terminal velocity W versus droplet size d_0

- e) temperature $T = 20, 12$ and $4\text{ }^{\circ}\text{C}$
- f) water salinity $S = 30\text{ }^{\circ}/\text{oo}$ (seawater), $10\text{ }^{\circ}/\text{oo}$ (brackish water) and $0\text{ }^{\circ}/\text{oo}$ (fresh water)
- g) oil concentration in the column $C_o = 20, 50$ and 150 ppm
- h) oil introduction: surface film and subsurface parcels.

The various test runs carried out are summarized in Table III.1.

It is very likely that the oil viscosity ν_o and the oil-water interfacial tension σ_{ow} are important parameters regarding the break-up of oil droplets. The values of ν_o , σ_{ow} and the oil densities ρ_o are given in Table A.1 for the different oil types, weathering states and temperatures. The experiments are indicated by a run number. In some cases two runs with similar sets of parameters are performed to test for reproducibility or to repeat a run with suspicious results.

The Figures III.6 to III.58 show data from the LBPS for all experiments with (detectable) oil droplets in the size classes below $1000\text{ }\mu\text{m}$. The droplet distributions were measured by the LBPS every fifteen or twenty seconds, the data in the figures are restricted to specific times t_m after the start of the grid oscillation. Measurements with grid oscillation time $t_{\text{grid}} = 600\text{ s}$ were performed to obtain steady state conditions. LBPS data are given in the figures generally at $t_m = 1, 2, 4, 6, 8$ and 10 minutes if reliable data were available. From the measurements it is observed that it took about 5 minutes to obtain the steady state for the droplet size distribution $d_o(f)$, an example is shown in Figure III.5b. Measurements with $t_{\text{grid}} = 5\text{ s}$ simulated the effect of short-duration turbulence from a single breaking wave. Data are given in the figures generally after $t_m = 30\text{ s}, 50\text{ s}, 1\frac{1}{2}$ and 2 minutes. The first distribution, at $t_m = 30\text{ s}$, shows the real droplet size distribution generated by the turbulence (for subsurface introduced oil). Subsequently measured distributions show the decrease of large oil droplets due to surfacing of these droplets, see e.g. Figure III.5a.

Table III-1. Summary of oil droplet break-up experiments in the grid column * ***

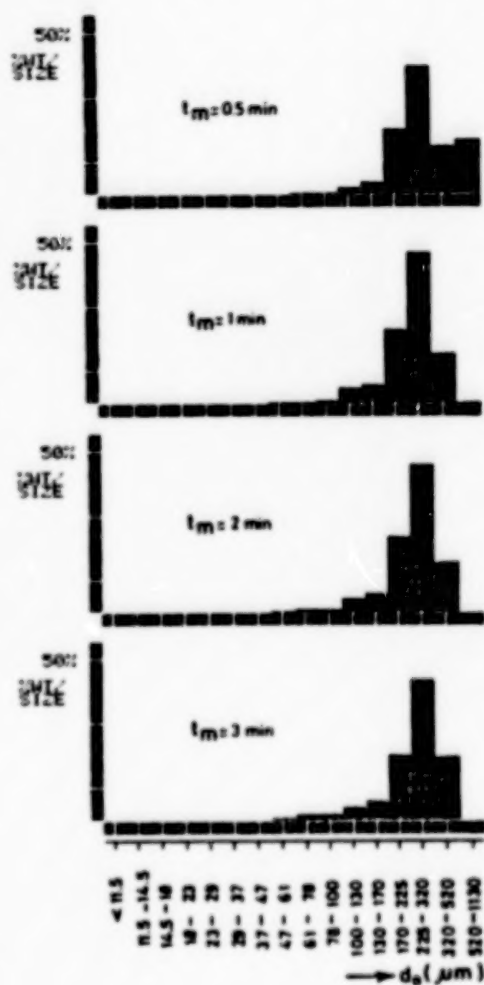
oil type, weathering state	temperature T(°C)	salinity S (‰)	Concentr. C ₀ (g/m ³)	1. subsurface spill 2. surface spill	energy dissipation rate ϵ (J/s m ³) and turbulence duration t_{grid}												
					$\epsilon = 3500$		$\epsilon = 1450$		$\epsilon = 440$		$\epsilon = 185$		$\epsilon = 55$		7	0.85	0
					$t_{grid}(s)$		$t_{grid}(s)$		$t_{grid}(s)$		$t_{grid}(s)$		$t_{grid}(s)$		$t_{grid}(s)$	$t_{grid}(s)$	
					600	5	600	5	600	5	600	5	600	5	20	20	0
** E _{ko}	20	30	50	1	47/75	46	44	45/74	43	42/73	40/43	39	38	37	36	35	34
E _{ko}	12	30	50	1	33				32						31		30
E _{ko}	20	30	50	2			77		76								
** PB ₀	20	30	50	1	10/14	19/13			8/12	1/7/11			6	5	4	3	2
PB ₀	12	30	50	1	29				28						27		
PB ₀	4	30	50	1	72	70	71	68	69	67	66	65	64	63	62		
PB ₀	20	30	20	1	18				17	15							
PB ₀	20	30	150	1	20				19	16							
PB ₀	20	10	50	1	26				25						24		
PB ₀	20	0	50	1	23				22						21		
PB ₃	20	30	50	1	61	59			60	58					57		
PB ₁₀	20	30	50	1	56	54			55	53					48		
PB _{em}	20	30	50	1	84	83	81	82	80				79				

* The experiments are indicated by the run number

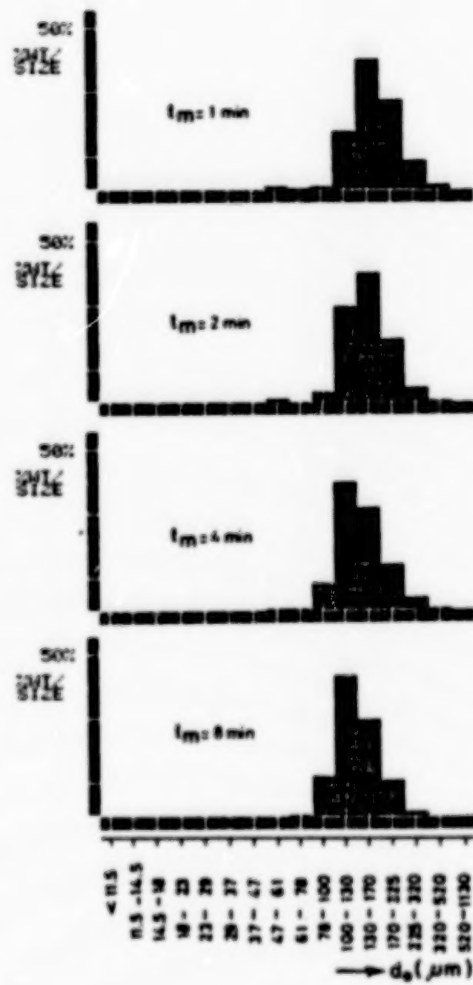
** Standard set of parameters. Varied values of the parameters are indicated by a square around the parameter in the second through sixth column.

*** Two or three run numbers at one set of variables indicate reproducibility experiments

64



a)



b)

FIGURE III. 5 Examples of LBPS data ($PB_{0,e} = 3500 \text{ J/s m}^3$)

a. experiment C13, $t_{\text{grid}} = 5 \text{ s}$

b. experiment C14, $t_{\text{grid}} = 600 \text{ s}$



$t_m = 0.5 \text{ min.}$

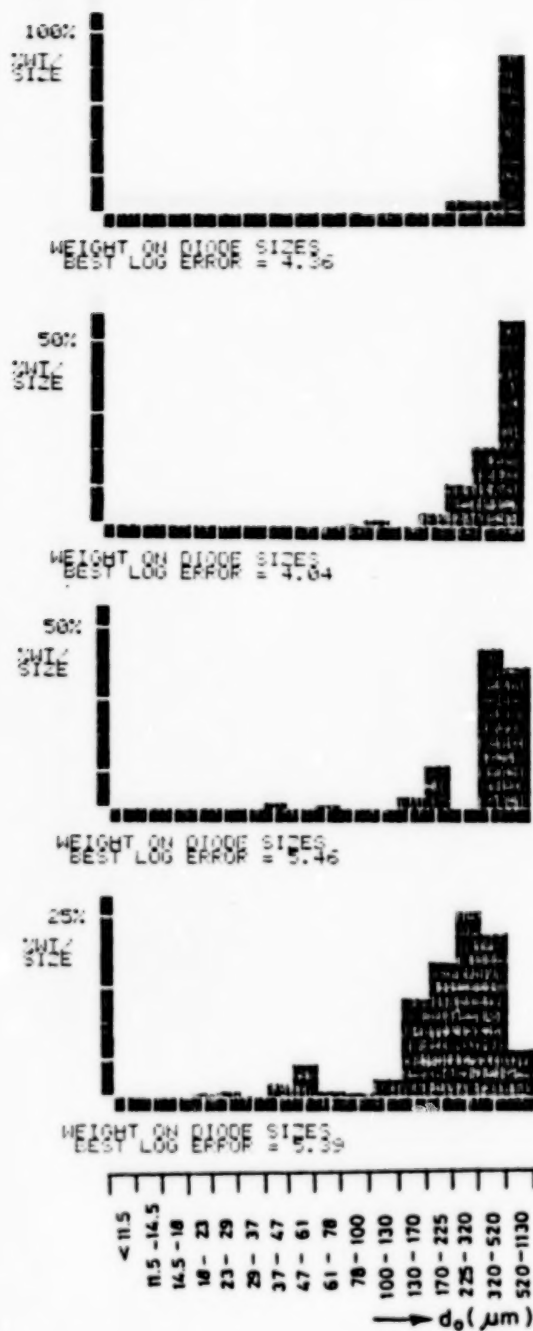


$t_m = 50 \text{ s}$

<13 13-14.5 14.5-16 16-23 23-29 29-37 37-47 47-61 61-78 78-100 100-130 130-170 170-225 225-320 320-520 520-1130
 → $d_o (\mu\text{m})$

RUN	OIL WEATHERING
C1	PB ₀
OIL SUPPLY	SUBSURFACE
TURBULENCE LEVEL	$e = 440 \text{ J/sm}^3$
GRID OSCILLATION	$t_{\text{grid}} = 5 \text{ s}$
TEMPERATURE	$T = 20 \text{ }^\circ\text{C}$
SALINITY	$S = 30 \text{ }^\circ\text{‰}$
OIL CONCENTRATION	$C = 50 \text{ ppm}$

FIGURE III.6 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 0.5 \text{ min.}$

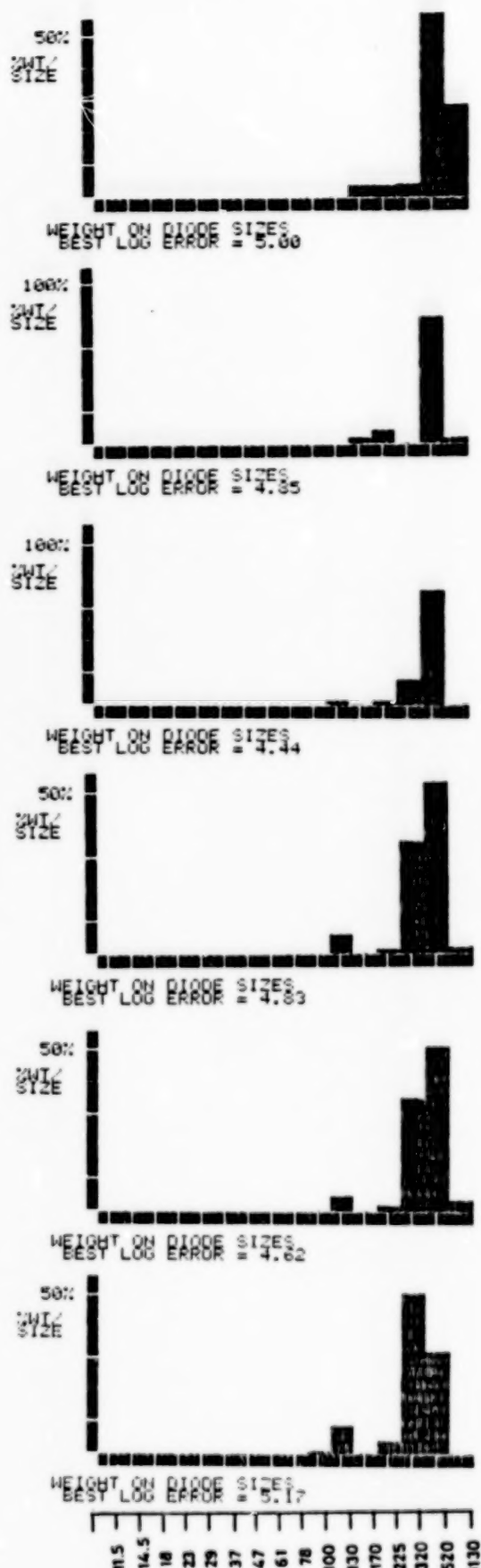
$t_m = 50 \text{ s}$

$t_m = 1.5 \text{ min}$

$t_m = 2 \text{ min.}$

RUN	OIL WEATHERING
C 7	PB ₀
OIL SUPPLY	SUBSURFACE
TURBULENCE LEVEL	$e = 440 \text{ J/sm}^3$
GRID OSCILLATION	$t_{\text{grid}} = 5 \text{ s}$
TEMPERATURE	$T = 20 \text{ }^\circ\text{C}$
SALINITY	$S = 30 \text{ }^\circ\text{‰}$
OIL CONCENTRATION	$C = 50 \text{ ppm}$

FIGURE III. 7 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

$t_m = 2 \text{ min.}$

$t_m = 4 \text{ min.}$

$t_m = 6 \text{ min.}$

$t_m = 8 \text{ min.}$

$t_m = 10 \text{ min.}$

RUN	OIL WEATHERING
C 8	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 8 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 0.5 \text{ min.}$



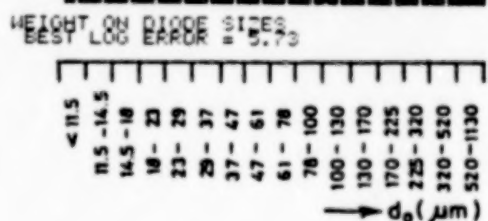
$t_m = 50 \text{ s}$



$t_m = 1.5 \text{ min}$



$t_m = 2 \text{ min.}$



RUN	OIL, WEATHERING
C9	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 5 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 9 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

WEIGHT ON DROPE SIZES
BEST LOG ERROR = 4.88



$t_m = 2 \text{ min.}$

WEIGHT ON DROPE SIZES
BEST LOG ERROR = 5.84



$t_m = 4 \text{ min.}$

WEIGHT ON DROPE SIZES
BEST LOG ERROR = 4.82



$t_m = 6 \text{ min.}$

WEIGHT ON DROPE SIZES
BEST LOG ERROR = 4.77



$t_m = 8 \text{ min.}$

WEIGHT ON DROPE SIZES
BEST LOG ERROR = 4.67



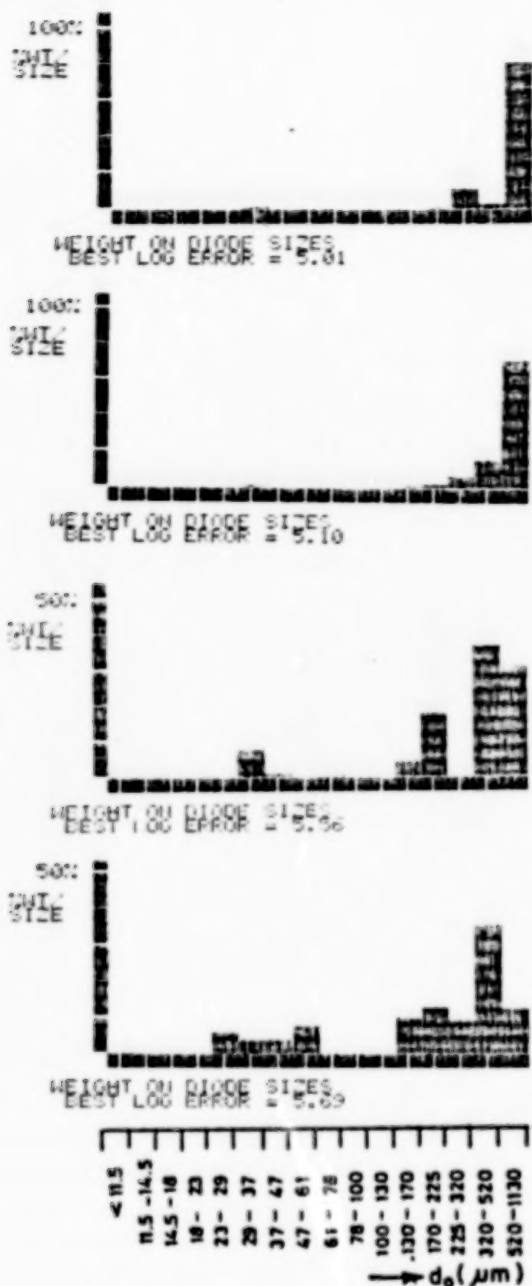
$t_m = 10 \text{ min.}$

WEIGHT ON DROPE SIZES
BEST LOG ERROR = 4.50

< 11.5
 $11.5 - 14.5$
 $14.5 - 18$
 $18 - 23$
 $23 - 29$
 $29 - 37$
 $37 - 47$
 $47 - 61$
 $61 - 78$
 $78 - 100$
 $100 - 130$
 $130 - 170$
 $170 - 225$
 $225 - 320$
 $320 - 520$
 $520 - 1130$

RUN	OIL WEATHERING
C 10	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 10 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 0.5 \text{ min.}$

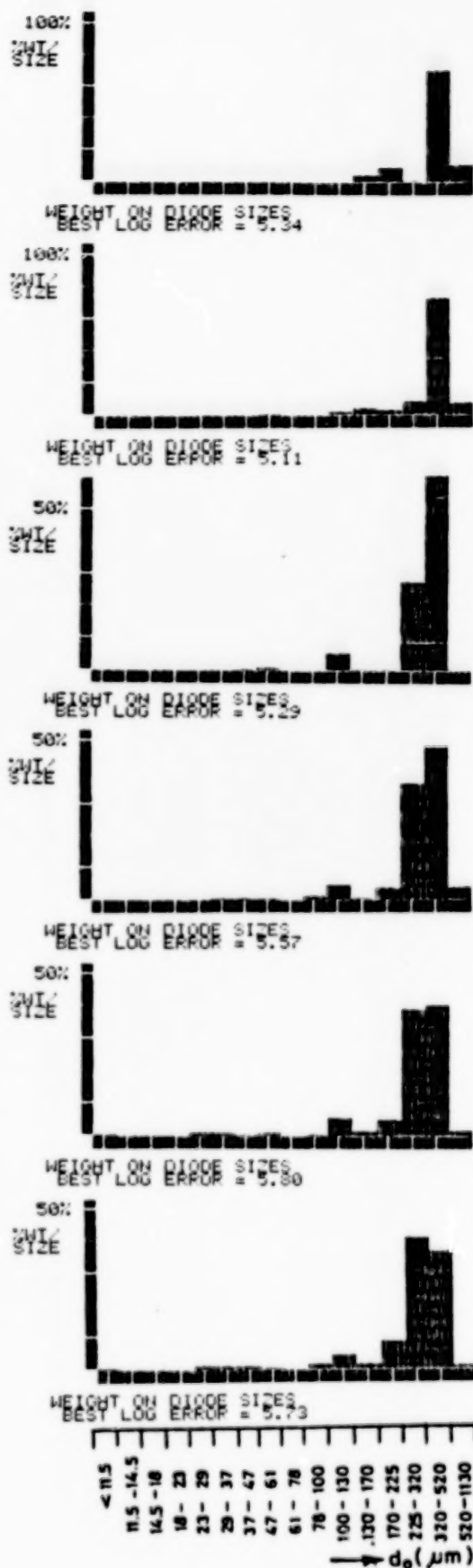
$t_m = 50 \text{ s}$

$t_m = 1.5 \text{ min.}$

$t_m = 2 \text{ min.}$

RUN	OIL WEATHERING
C 11	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 5 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 11 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

$t_m = 2 \text{ min.}$

$t_m = 4 \text{ min.}$

$t_m = 6 \text{ min.}$

$t_m = 8 \text{ min.}$

$t_m = 10 \text{ min.}$

RUN	OIL WEATHERING
C 12	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 12 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 0.5 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.31



$t_m = 50 \text{ s}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.33



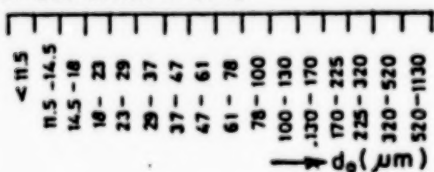
$t_m = 1.5 \text{ min}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.40



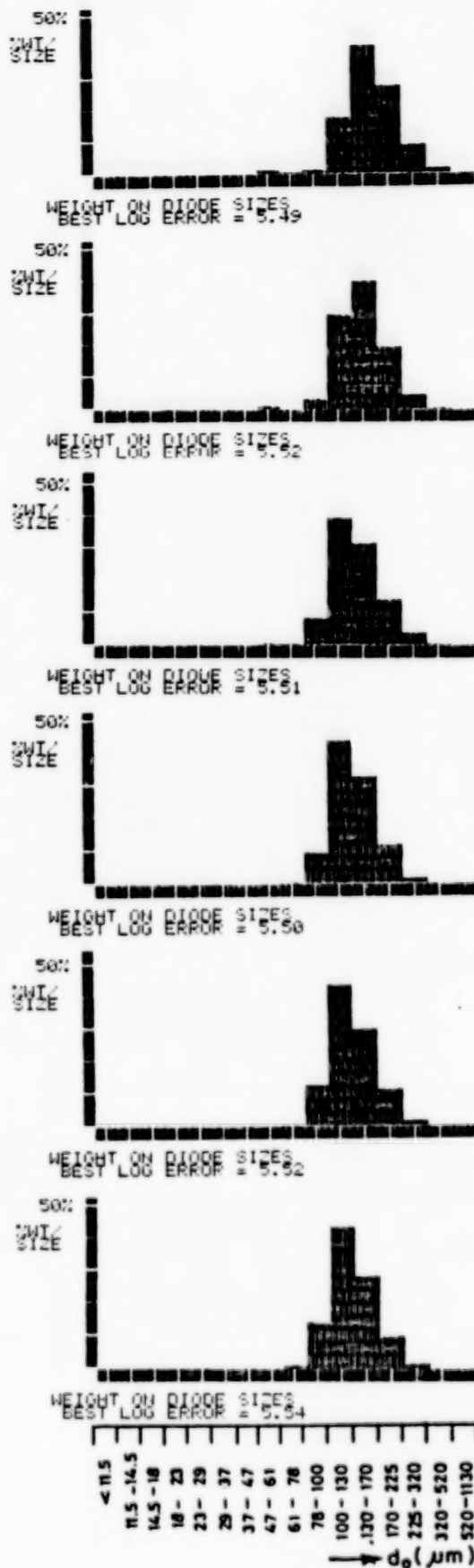
$t_m = 2 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.42



RUN	OIL WEATHERING
C 13	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 5 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 13 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1$ min.

$t_m = 2$ min.

$t_m = 4$ min.

$t_m = 6$ min.

$t_m = 8$ min.

$t_m = 10$ min.

RUN	OIL, WEATHERING
C 14	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III.14 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN AT TIME t_m . LBPS DATA



$t_m = 0.5 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.80



$t_m = 50 \text{ s}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.01



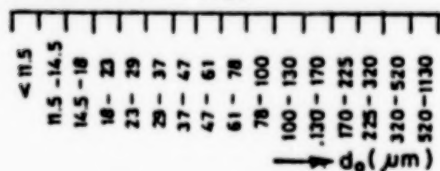
$t_m = 1.5 \text{ min}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.47



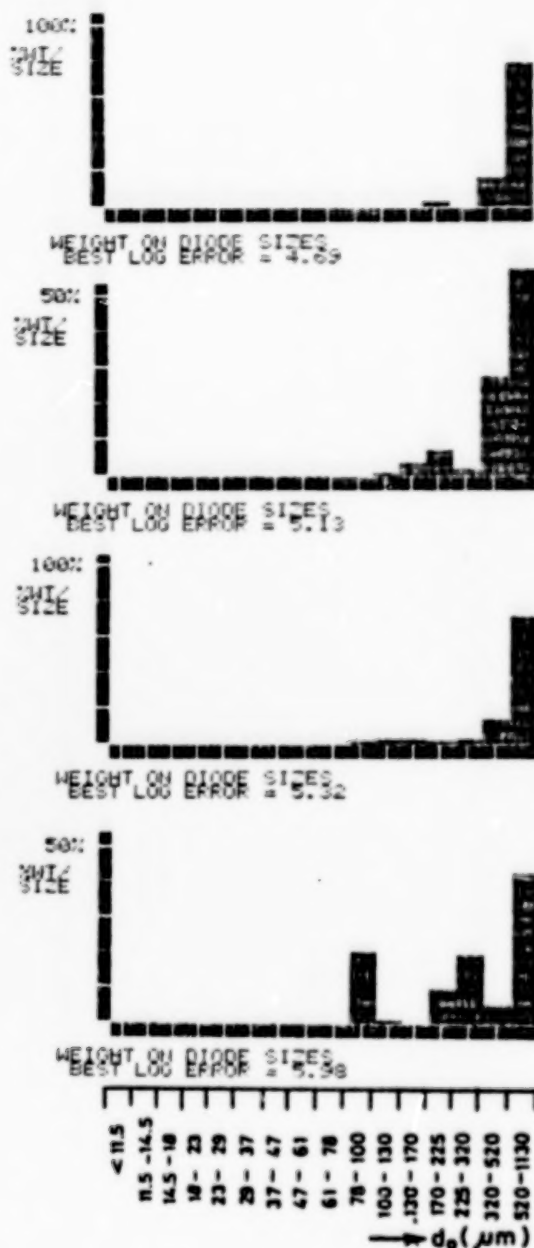
$t_m = 2 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.23



RUN	OIL WEATHERING
C 15	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 5 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 20 \text{ ppm}$	

FIGURE III. 15 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 0.5 \text{ min}$

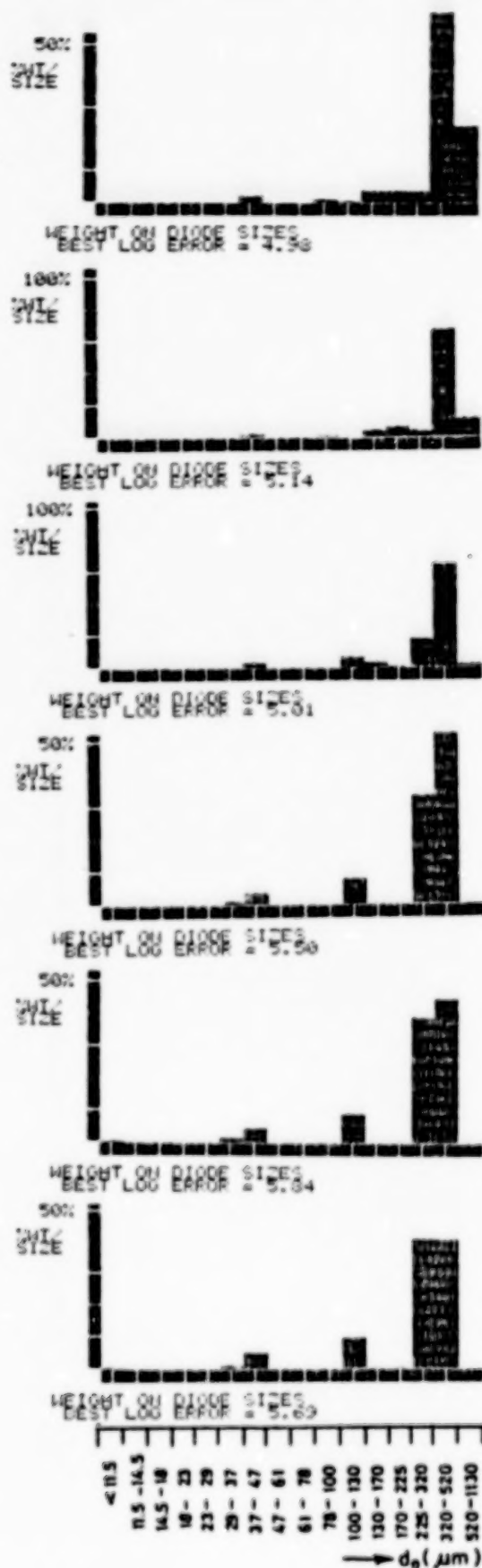
$t_m = 50 \text{ s}$

$t_m = 1.5 \text{ min}$

$t_m = 2 \text{ min}$

RUN	OIL WEATHERING
C 16	PB ₀
OIL SUPPLY	SUBSURFACE
TURBULENCE LEVEL	$e = 440 \text{ J/sm}^3$
GRID OSCILLATION	$t_{\text{grid}} = 5 \text{ s}$
TEMPERATURE	$T = 20 \text{ }^\circ\text{C}$
SALINITY	$S = 30 \text{ }^\circ\text{‰}$
OIL CONCENTRATION	$C = 150 \text{ ppm}$

FIGURE III.16 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1$ min.

$t_m = 2$ min.

$t_m = 4$ min.

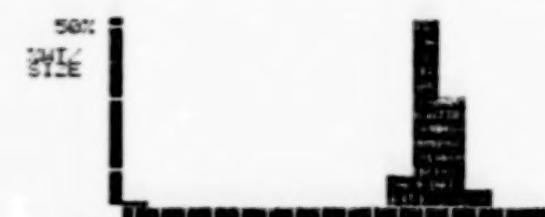
$t_m = 6$ min.

$t_m = 8$ min.

$t_m = 10$ min.

RUN	OIL WEATHERING
C 19	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 150 \text{ ppm}$	

FIGURE III.18 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN AT TIME t_m . LBPS DATA



HEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.06

$t_m = 1 \text{ min.}$



HEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.49

$t_m = 2 \text{ min.}$



HEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.35

$t_m = 4 \text{ min.}$



HEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.22

$t_m = 6 \text{ min.}$



HEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.22

$t_m = 8 \text{ min.}$



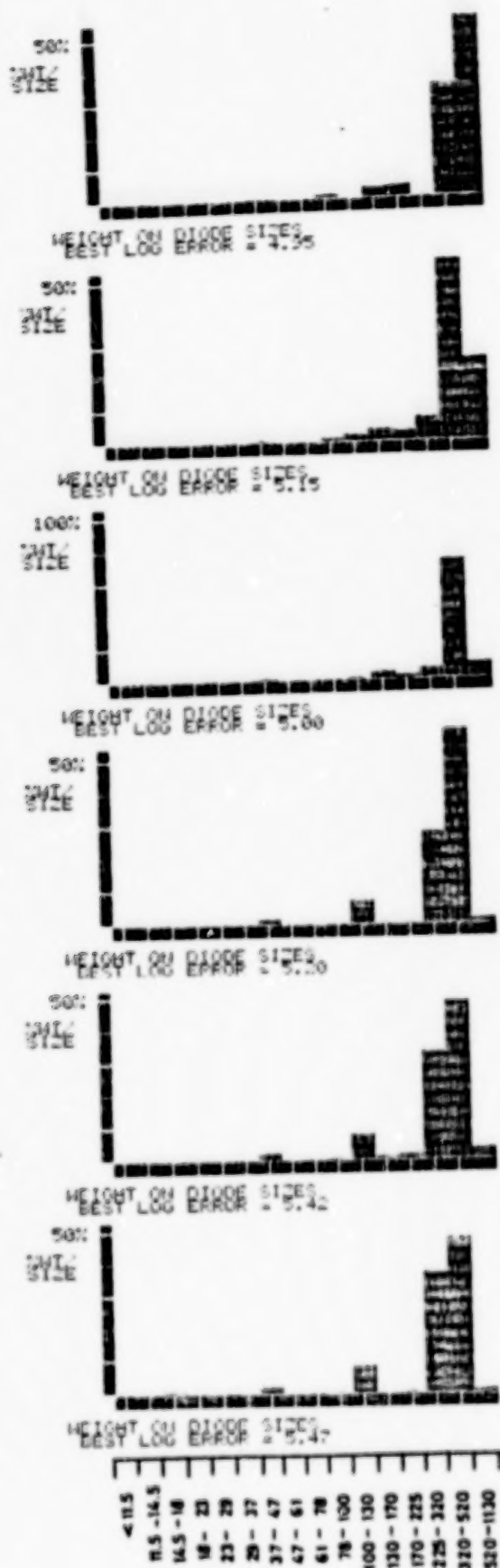
HEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.20

$t_m = 10 \text{ min.}$

< 11.5
 $11.5 - 14.5$
 $14.5 - 18$
 $18 - 23$
 $23 - 29$
 $29 - 37$
 $37 - 47$
 $47 - 61$
 $61 - 78$
 $78 - 100$
 $100 - 130$
 $130 - 170$
 $170 - 225$
 $225 - 320$
 $320 - 520$
 $520 - 1130$

RUN	OIL WEATHERING
C 20	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/m}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 150 \text{ ppm}$	

FIGURE III. 19 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

$t_m = 2 \text{ min.}$

$t_m = 4 \text{ min.}$

$t_m = 6 \text{ min.}$

$t_m = 8 \text{ min.}$

$t_m = 10 \text{ min.}$

RUN	OIL WEATHERING
C 22	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 7.0$	J/sm ³
GRID OSCILLATION	
$t_{\text{grid}} = 20 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^{\circ}\text{C}$	
SALINITY	
$S = 0 \text{ }_{\text{‰}}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 20 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

WEIGHT ON DROPLE SIZES
BEST LOG ERROR = 5.62



$t_m = 2 \text{ min.}$

WEIGHT ON DROPLE SIZES
BEST LOG ERROR = 4.36



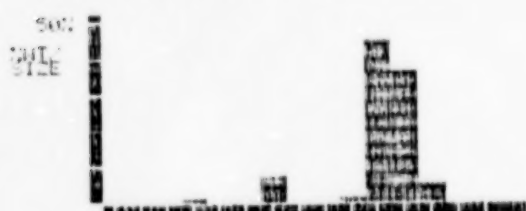
$t_m = 4 \text{ min.}$

WEIGHT ON DROPLE SIZES
BEST LOG ERROR = 5.13



$t_m = 6 \text{ min.}$

WEIGHT ON DROPLE SIZES
BEST LOG ERROR = 5.25



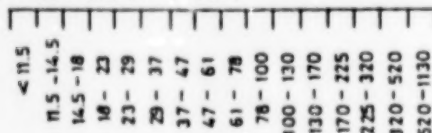
$t_m = 8 \text{ min.}$

WEIGHT ON DROPLE SIZES
BEST LOG ERROR = 5.24



$t_m = 10 \text{ min.}$

WEIGHT ON DROPLE SIZES
BEST LOG ERROR = 5.30



RUN	OIL WEATHERING
C 23	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 0 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 21 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.83



$t_m = 2 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.91



$t_m = 4 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.81



$t_m = 6 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.00



$t_m = 8 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.10



$t_m = 10 \text{ min.}$

WEIGHT ON DIODE SIZES

11.5 14.5 18 22 29 37 47 61 78 100 130 170 225 320 520 1130

RUN	OIL WEATHERING
C 25	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 10 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 22 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$



$t_m = 2 \text{ min.}$



$t_m = 4 \text{ min.}$



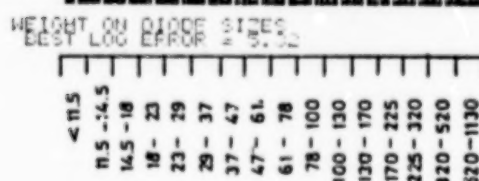
$t_m = 6 \text{ min.}$



$t_m = 8 \text{ min.}$

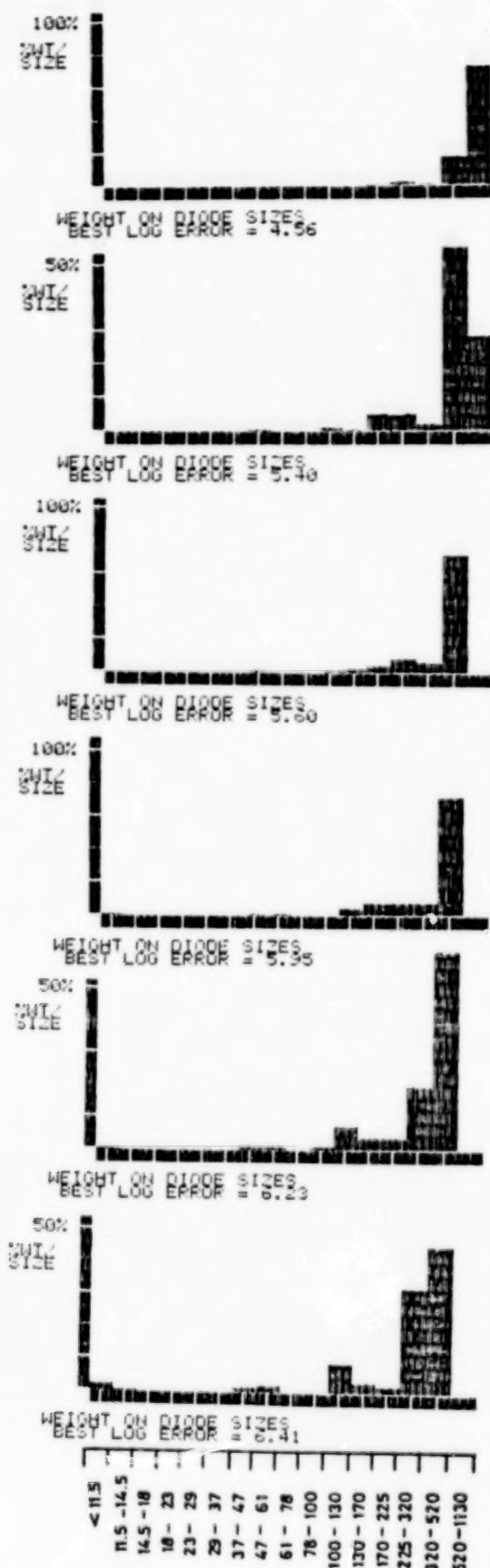


$t_m = 10 \text{ min.}$



RUN	OIL WEATHERING
C 26	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 10 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 23 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

$t_m = 2 \text{ min.}$

$t_m = 4 \text{ min.}$

$t_m = 6 \text{ min.}$

$t_m = 8 \text{ min.}$

$t_m = 10 \text{ min.}$

RUN	OIL WEATHERING
C 28	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 12 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III.24 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.03



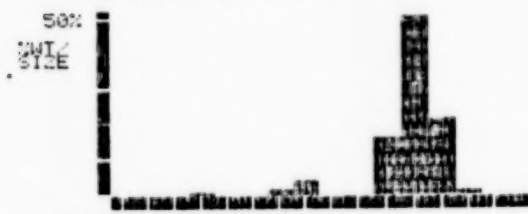
$t_m = 2 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.24



$t_m = 4 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.06



$t_m = 6 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.02



$t_m = 8 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.24



$t_m = 10 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.23

< 11.5
11.5 - 14.5
14.5 - 18
18 - 23
23 - 29
29 - 37
37 - 47
47 - 61
61 - 78
78 - 100
100 - 130
130 - 170
170 - 225
225 - 320
320 - 520
520 - 1130

RUN	OIL WEATHERING
C 29	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 12 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 25 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.86



$t_m = 2 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.86



$t_m = 4 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.30



$t_m = 6 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.61



$t_m = 8 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.61



$t_m = 11 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.93

< 11.5
11.5 - 14.5
14.5 - 18
18 - 23
23 - 29
29 - 37
37 - 47
47 - 61
61 - 78
78 - 100
100 - 130
130 - 170
170 - 225
225 - 320
320 - 520
520 - 1130

RUN	OIL WEATHERING
C 32	Eko
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 12 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 26 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.85

$t_m = 1 \text{ min.}$



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.67

$t_m = 2 \text{ min.}$



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.92

$t_m = 4 \text{ min.}$



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.28

$t_m = 6 \text{ min.}$



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.33

$t_m = 8 \text{ min.}$



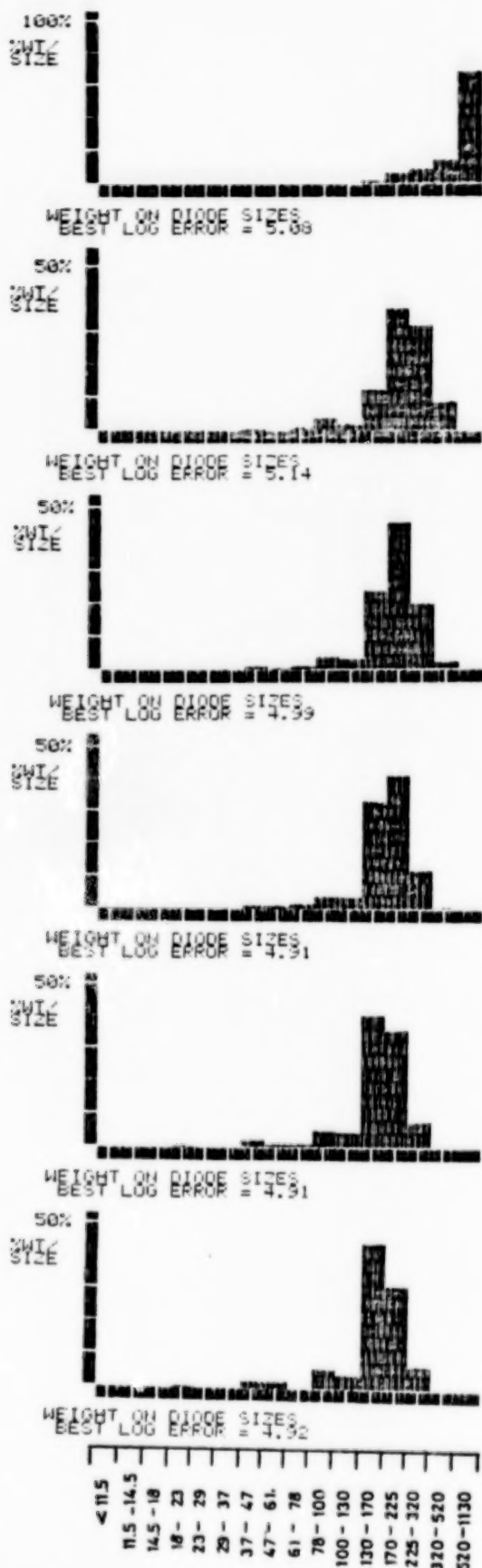
WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.35

$t_m = 10 \text{ min.}$

< 11.5
11.5 - 14.5
14.5 - 18
18 - 23
23 - 29
29 - 37
37 - 47
47 - 61
61 - 78
78 - 100
100 - 130
130 - 170
170 - 225
225 - 320
320 - 520
520 - 1130

RUN	OIL WEATHERING
C 33	Eko
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 12 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 27 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

$t_m = 2 \text{ min.}$

$t_m = 4 \text{ min.}$

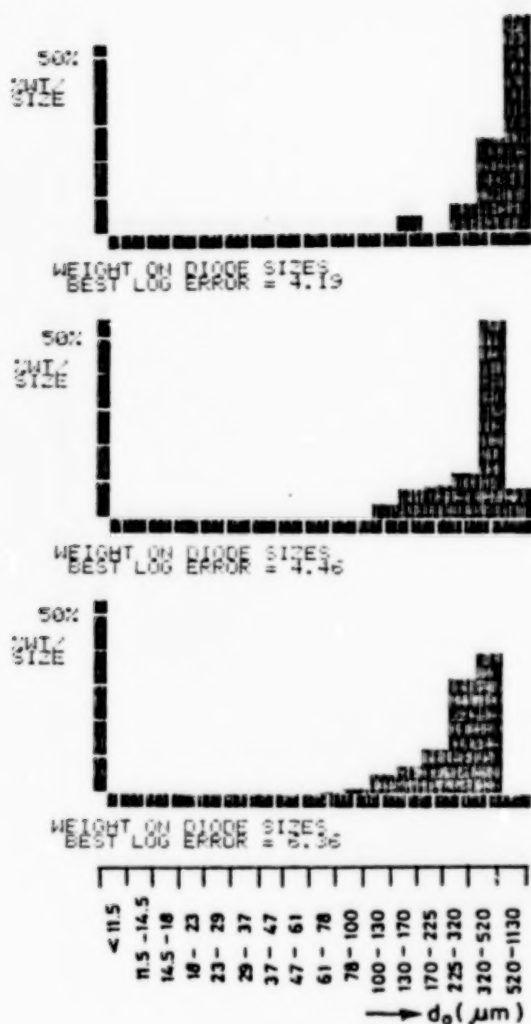
$t_m = 6 \text{ min.}$

$t_m = 8 \text{ min.}$

$t_m = 10 \text{ min.}$

RUN	OIL WEATHERING
C 41	Eko
OIL SUPPLY	SUBSURFACE
TURBULENCE LEVEL	$e = 440 \text{ J/sm}^3$
GRID OSCILLATION	$t_{\text{grid}} = 600 \text{ s}$
TEMPERATURE	$T = 20 \text{ }^\circ\text{C}$
SALINITY	$S = 30 \text{ }^\circ\text{‰}$
OIL CONCENTRATION	$C = 50 \text{ ppm}$

FIGURE III. 28 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 0.5 \text{ min.}$

$t_m = 1 \text{ min.}$

$t_m = 1.5 \text{ min.}$

RUN	OIL WEATHERING
C 42	Eko
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 5 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 29 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$



$t_m = 2 \text{ min.}$



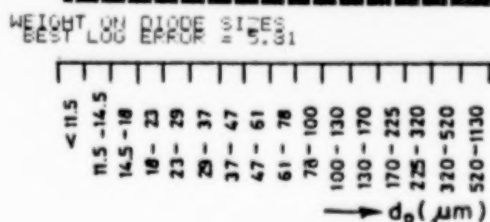
$t_m = 4 \text{ min.}$



$t_m = 6 \text{ min.}$



$t_m = 8 \text{ min.}$



RUN	OIL, WEATHERING
C 43	Eko
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 185 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 30 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.99



$t_m = 2 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.10



$t_m = 4 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.97



$t_m = 6 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.91



$t_m = 8 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.81



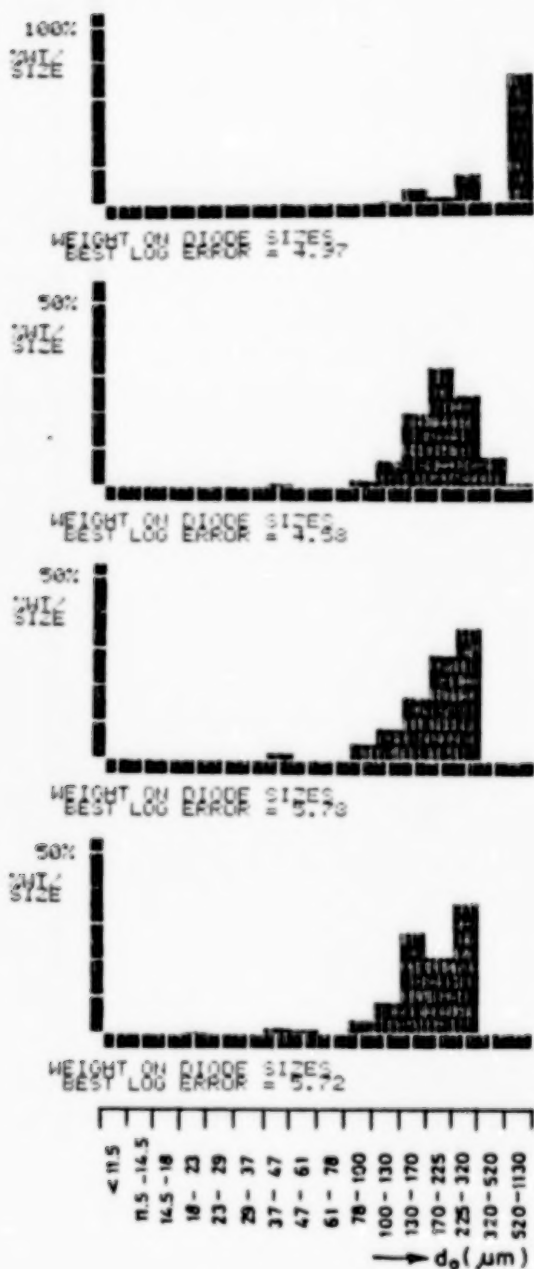
$t_m = 10 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.76

< 11.5
11.5 - 14.5
14.5 - 18
18 - 23
23 - 29
29 - 37
37 - 47
47 - 61
61 - 78
78 - 100
100 - 130
130 - 170
170 - 225
225 - 320
320 - 520
520 - 1130

RUN	OIL WEATHERING
C 44	Eko
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 1480 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 31 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 0.5 \text{ min}$

$t_m = 1 \text{ min}$

$t_m = 1.5 \text{ min}$

$t_m = 2 \text{ min}$

RUN	OIL WEATHERING
C 45	Eko
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 1480 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 5 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 32 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN AT TIME t_m . LBPS DATA



$t_m = 0.5 \text{ min}$



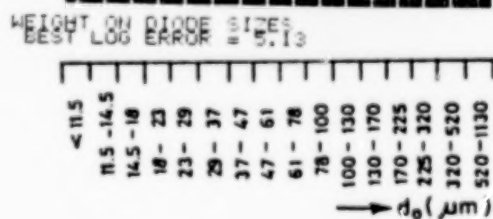
$t_m = 1 \text{ min}$



$t_m = 1.5 \text{ min}$



$t_m = 2 \text{ min}$

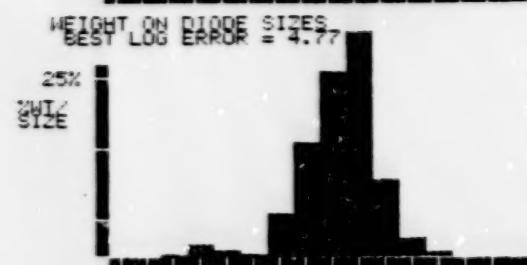


RUN	OIL, WEATHERING
C 46	Eko
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 5 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

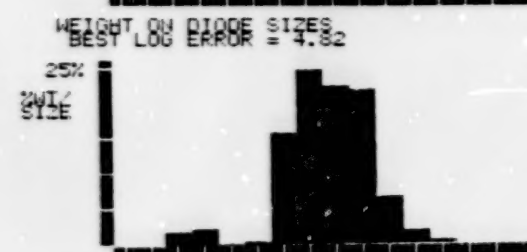
FIGURE III. 33 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$



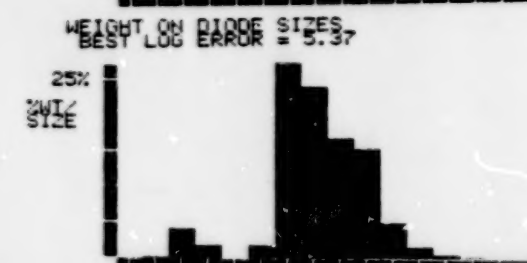
$t_m = 2 \text{ min.}$



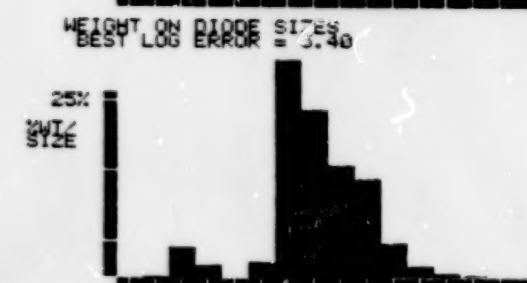
$t_m = 4 \text{ min.}$



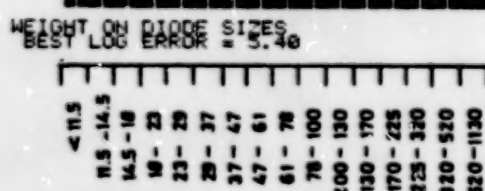
$t_m = 6 \text{ min.}$



$t_m = 8 \text{ min.}$



$t_m = 10 \text{ min.}$



RUN	OIL WEATHERING
C 47	Eko
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 34 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 0.5 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.00



$t_m = 1 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.89



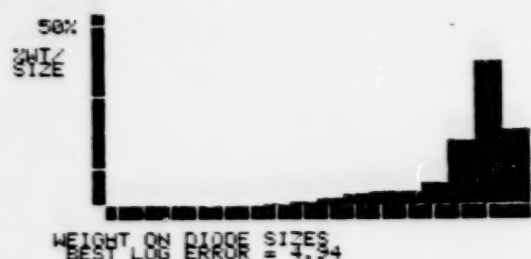
$t_m = 1.5 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.16



RUN	OIL WEATHERING
C 53	PB ₁₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 5 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 35 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 0.5 \text{ min.}$



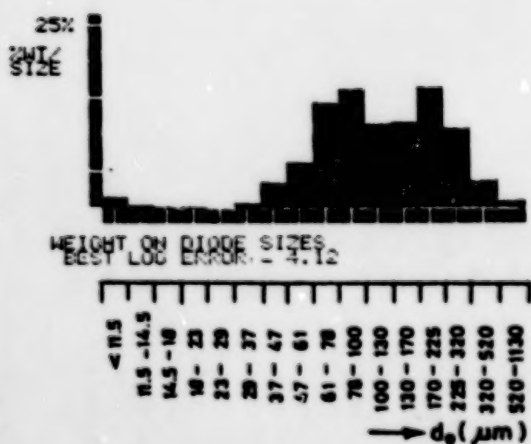
$t_m = 1 \text{ min.}$



$t_m = 1.5 \text{ min.}$



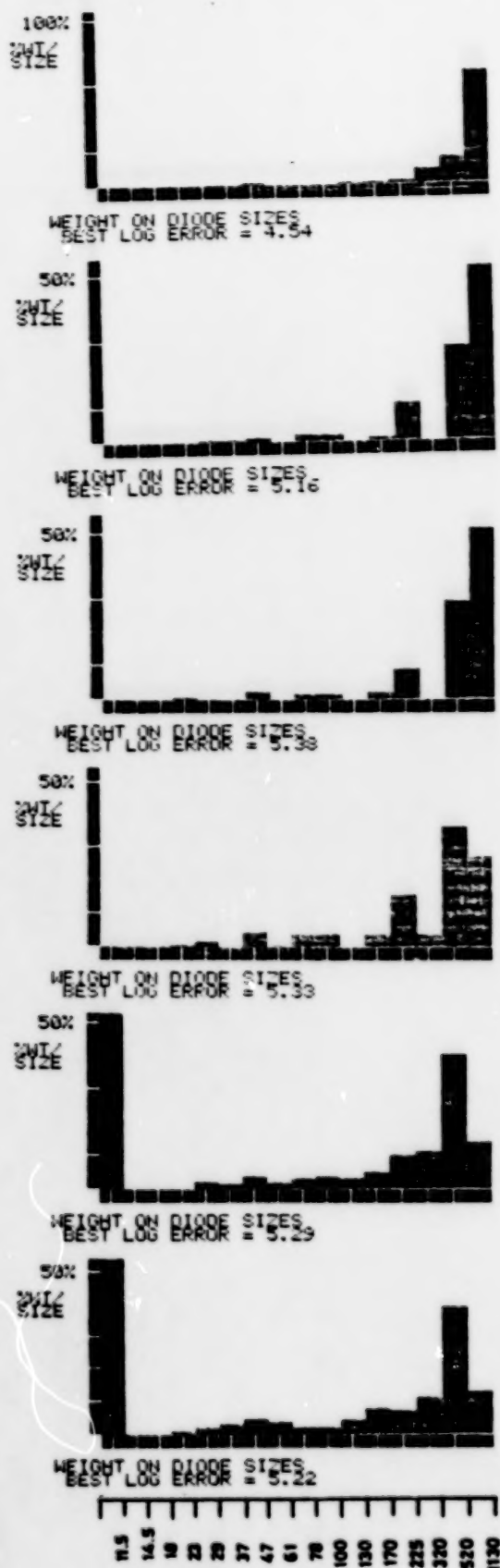
$t_m = 2 \text{ min.}$



$t_m = 7.5 \text{ min.}$

RUN	OIL, WEATHERING
C 54	PB ₁₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 5 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 36 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

$t_m = 2 \text{ min.}$

$t_m = 4 \text{ min.}$

$t_m = 6 \text{ min.}$

$t_m = 8 \text{ min.}$

$t_m = 10 \text{ min.}$

RUN	OIL WEATHERING
C 55	PB ₁₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 37 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.13



$t_m = 2 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.12



$t_m = 4 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.86



$t_m = 6 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.73



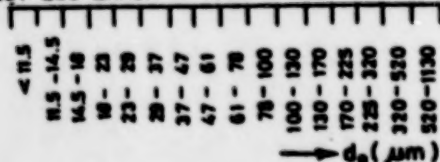
$t_m = 8 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.69



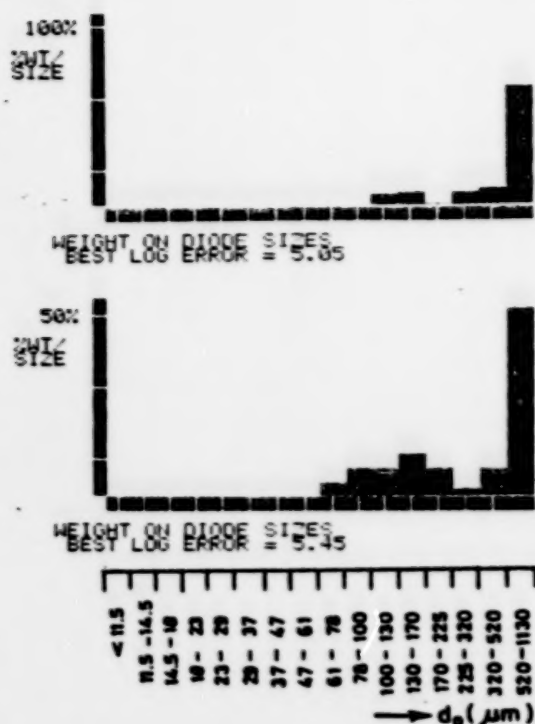
$t_m = 10 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.61



RUN	OIL, WEATHERING
C 56	PB ₁₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 38 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 0.5 \text{ min.}$

$t_m = 1 \text{ min.}$

RUN	OIL, WEATHERING
C 58	PB ₃
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 5 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 39 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.38

$t_m = 0.5 \text{ min.}$



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.32

$t_m = 1 \text{ min.}$



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.41

$t_m = 1.5 \text{ min.}$



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.31

$t_m = 2 \text{ min.}$



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.64

$t_m = 4.5 \text{ min.}$

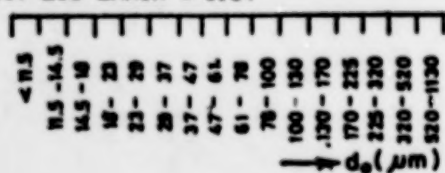
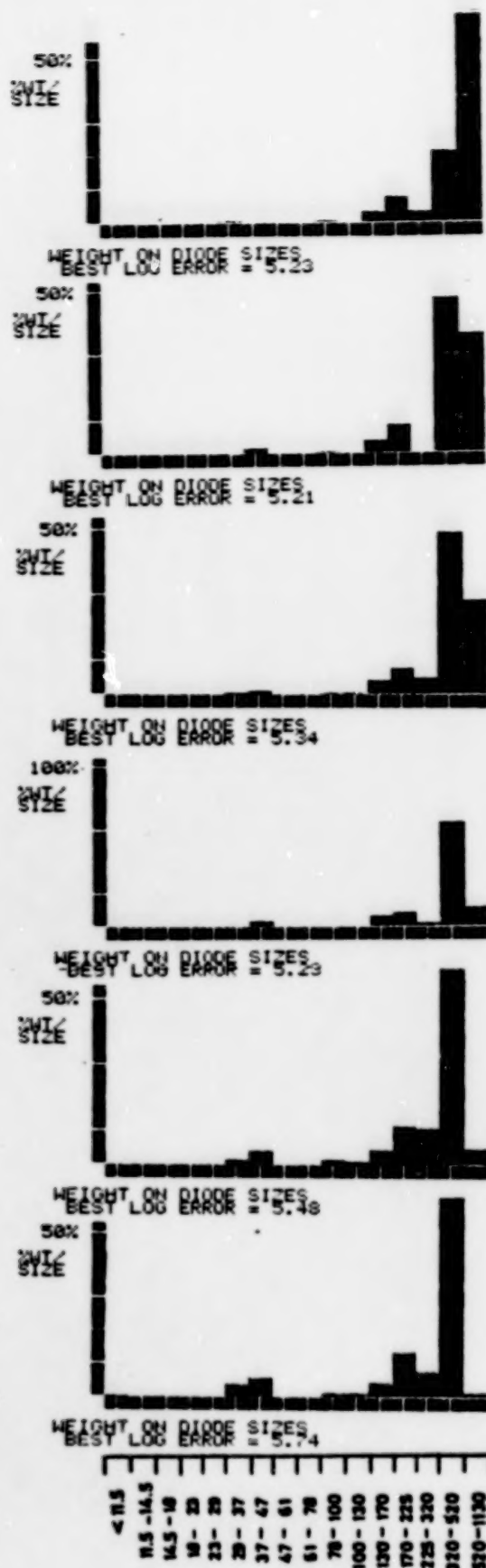


FIGURE III. 40 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA

RUN	OIL WEATHERING
C 59	PB ₃
OIL SUPPLY	SUBSURFACE
TURBULENCE LEVEL	$e = 3500 \text{ J/sm}^3$
GRID OSCILLATION	$t_{\text{grid}} = 5 \text{ s}$
TEMPERATURE	$T = 20 \text{ }^\circ\text{C}$
SALINITY	$S = 30 \text{ }^\circ\text{‰}$
OIL CONCENTRATION	$C = 50 \text{ ppm}$



$t_m = 1 \text{ min.}$

$t_m = 2 \text{ min.}$

$t_m = 4 \text{ min.}$

$t_m = 6 \text{ min.}$

$t_m = 8 \text{ min.}$

$t_m = 10 \text{ min.}$

RUN	OIL WEATHERING
C 60	PB ₃
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 41 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.88



$t_m = 2 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.65



$t_m = 4 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.62



$t_m = 6 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.53



$t_m = 8 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.20



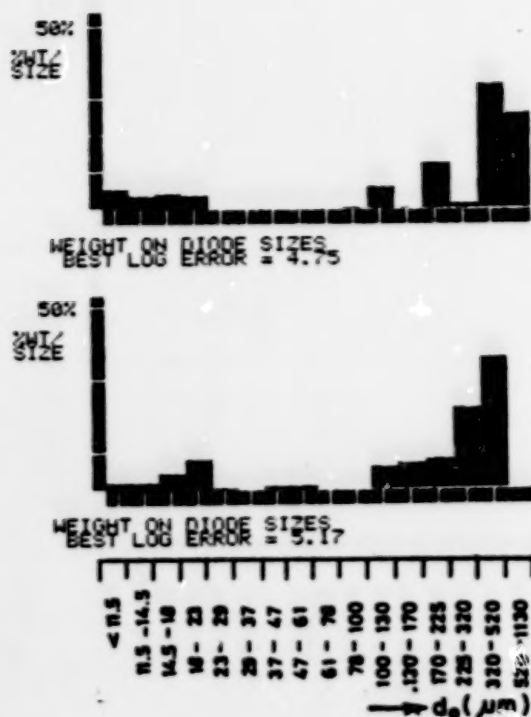
$t_m = 10 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.21



RUN	OIL WEATHERING
C 61	PB 3
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 42 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



RUN	OIL, WEATHERING
C 68	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 1480 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 5 \text{ s}$	
TEMPERATURE	
$T = 4 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 43 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



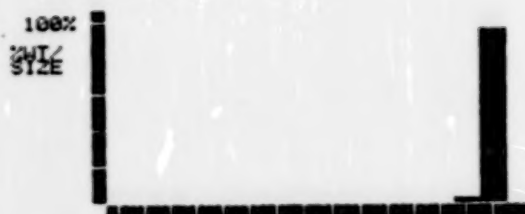
$t_m = 0.5 \text{ min.}$

WEIGHT ON DROPLET SIZES
BEST LOG ERROR = 5.85



$t_m = 2 \text{ min.}$

WEIGHT ON DROPLET SIZES
BEST LOG ERROR = 6.54



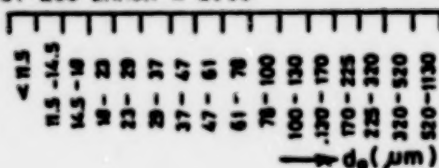
$t_m = 4 \text{ min.}$

WEIGHT ON DROPLET SIZES
BEST LOG ERROR = 6.54



$t_m = 6 \text{ min.}$

WEIGHT ON DROPLET SIZES
BEST LOG ERROR = 6.19



RUN	OIL, WEATHERING
C 69	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 4 \text{ C}$	
SALINITY	
$S = 30 \text{ ‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 44 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 0.5 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.99



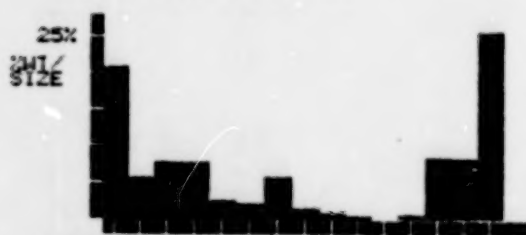
$t_m = 1 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.13



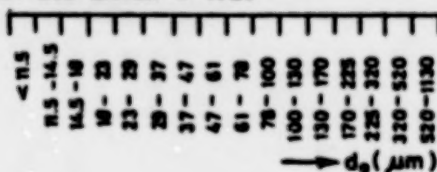
$t_m = 1.5 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.71



$t_m = 2 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.21

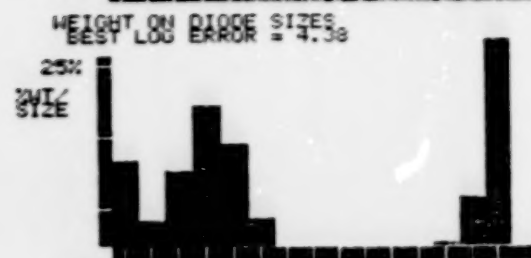


RUN	OIL, WEATHERING
C 70	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 5 \text{ s}$	
TEMPERATURE	
$T = 4^\circ \text{C}$	
SALINITY	
$S = 30 \text{ ‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

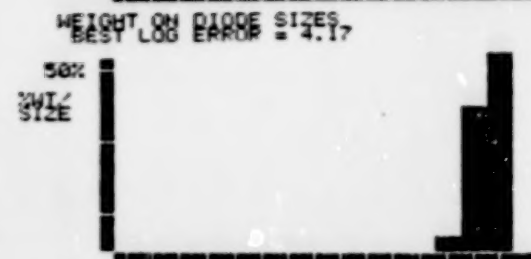
FIGURE III. 45 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



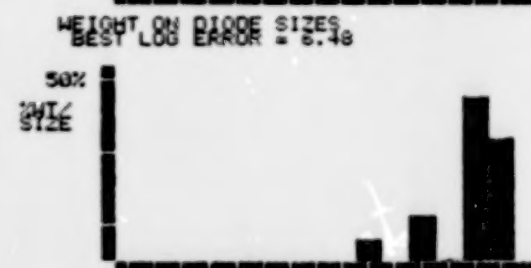
$t_m = 0.5 \text{ min.}$



$t_m = 2 \text{ min.}$



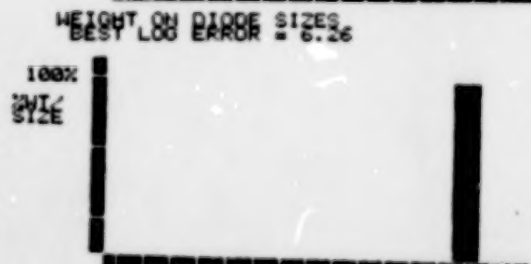
$t_m = 4 \text{ min.}$



$t_m = 6 \text{ min.}$



$t_m = 8 \text{ min.}$



$t_m = 10 \text{ min.}$



RUN	OIL, WEATHERING
C 71	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 1480 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 4 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 46 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.30



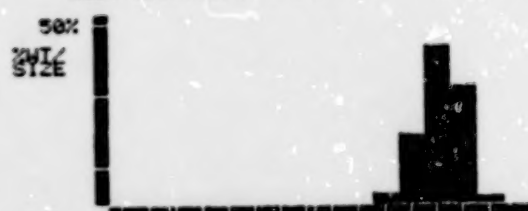
$t_m = 2 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.33



$t_m = 4 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.30



$t_m = 6 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.23



$t_m = 8 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.33



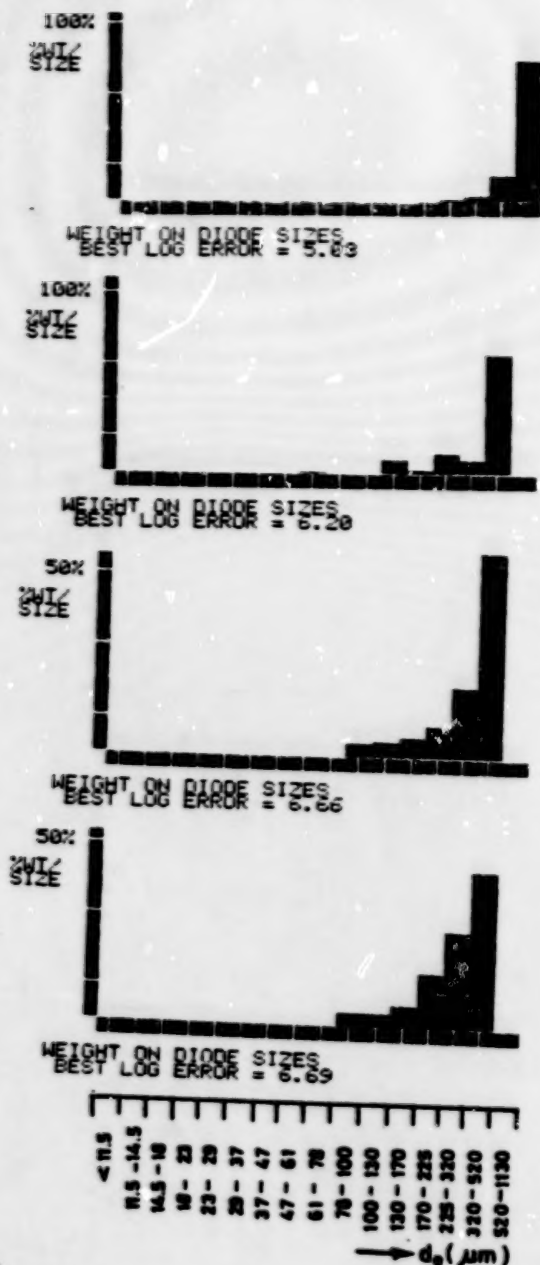
$t_m = 10 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.35



RUN	OIL, WEATHERING
C 72	PB ₀
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 4 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 47 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 0.5 \text{ min.}$

$t_m = 1 \text{ min.}$

$t_m = 1.5 \text{ min.}$

$t_m = 2 \text{ min.}$

RUN	OIL, WEATHERING
C 73	Eko
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 5 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 48 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 0.5 \text{ min.}$



$t_m = 1 \text{ min.}$



$t_m = 1.5 \text{ min.}$



$t_m = 2 \text{ min.}$

μm
 11.5 14.5 18 23 28 37 47 61 78 100 130 170 225 320 520 1130
 $d_p (\mu m)$

RUN	OIL, WEATHERING
C 74	Eko
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 1480 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{grid} = 5 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 49 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$



$t_m = 2 \text{ min.}$



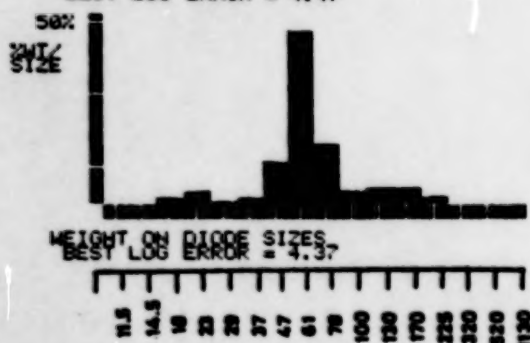
$t_m = 4 \text{ min.}$



$t_m = 6 \text{ min.}$



$t_m = 8 \text{ min.}$



$t_m = 10 \text{ min.}$

RUN	OIL, WEATHERING
C 75	Eko
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 3500 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 50 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.32

$t_m = 1 \text{ min.}$



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.26

$t_m = 2 \text{ min.}$



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.67

$t_m = 4 \text{ min.}$



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.11

$t_m = 6 \text{ min.}$



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.05

$t_m = 8 \text{ min.}$



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.97

$t_m = 10 \text{ min.}$

14.5 15 15.5 16 16.5 17 17.5 18 18.5 19 19.5 20 20.5 21 21.5 22 22.5 23 23.5 24 24.5 25 25.5 26 26.5 27 27.5 28 28.5 29 29.5 30 30.5 31 31.5 32 32.5 33 33.5 34 34.5 35 35.5 36 36.5 37 37.5 38 38.5 39 39.5 40 40.5 41 41.5 42 42.5 43 43.5 44 44.5 45 45.5 46 46.5 47 47.5 48 48.5 49 49.5 50 50.5 51 51.5 52 52.5 53 53.5 54 54.5 55 55.5 56 56.5 57 57.5 58 58.5 59 59.5 60 60.5 61 61.5 62 62.5 63 63.5 64 64.5 65 65.5 66 66.5 67 67.5 68 68.5 69 69.5 70 70.5 71 71.5 72 72.5 73 73.5 74 74.5 75 75.5 76 76.5 77 77.5 78 78.5 79 79.5 80 80.5 81 81.5 82 82.5 83 83.5 84 84.5 85 85.5 86 86.5 87 87.5 88 88.5 89 89.5 90 90.5 91 91.5 92 92.5 93 93.5 94 94.5 95 95.5 96 96.5 97 97.5 98 98.5 99 100

RUN	OIL, WEATHERING
C 76	Eko
OIL SUPPLY	
SURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
SURFACE LAYER	

FIGURE III. 51 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.82



$t_m = 2 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.86



$t_m = 4 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.33



$t_m = 6 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.24



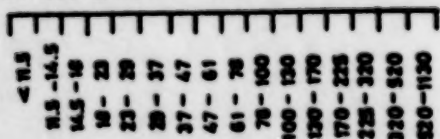
$t_m = 8 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.84



$t_m = 10 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.97

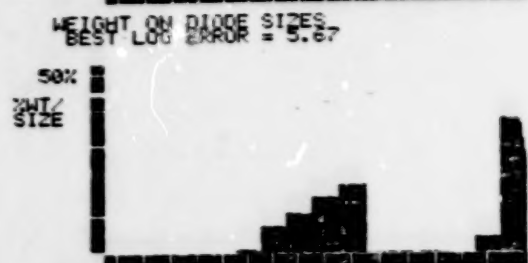


RUN	OIL, WEATHERING
C 77	Eko
OIL SUPPLY	SURFACE
TURBULENCE LEVEL	$e = 1480 \text{ J/sm}^3$
GRID OSCILLATION	$t_{\text{grid}} = 600 \text{ s}$
TEMPERATURE	$T = 20 \text{ }^\circ\text{C}$
SALINITY	$S = 30 \text{ }^\circ\text{‰}$
OIL CONCENTRATION	SURFACE LAYER

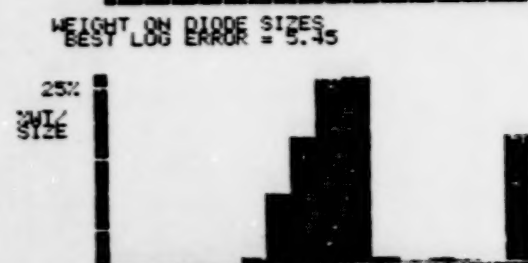
FIGURE III. 52 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



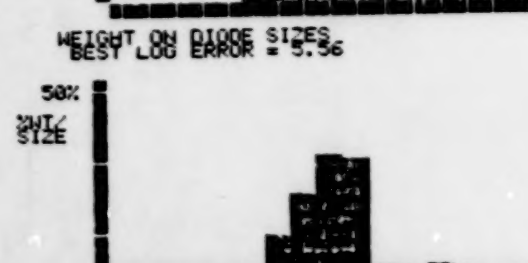
$t_m = 1 \text{ min.}$



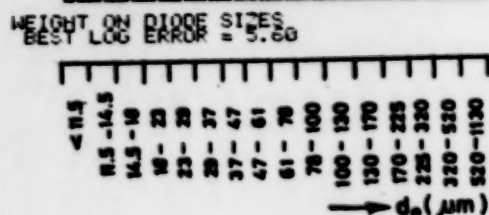
$t_m = 3 \text{ min.}$



$t_m = 4 \text{ min.}$



$t_m = 6 \text{ min.}$



RUN	OIL WEATHERING
C 79	PB _{em}
OIL SUPPLY	
	SUBSURFACE
TURBULENCE LEVEL	
	$e = 55 \text{ J/sm}^3$
GRID OSCILLATION	
	$t_{\text{grid}} = 600 \text{ s}$
TEMPERATURE	
	$T = 20 \text{ }^\circ\text{C}$
SALINITY	
	$S = 30 \text{ }^\circ\text{‰}$
OIL CONCENTRATION	
	$C = 50 \text{ ppm}$

FIGURE III. 53 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.95

$t_m = 2 \text{ min.}$



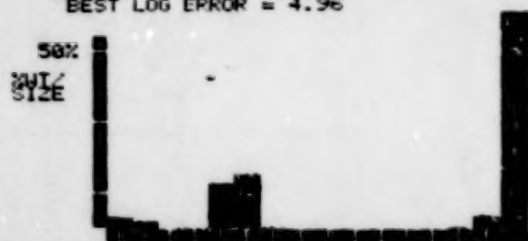
WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.21

$t_m = 3 \text{ min.}$



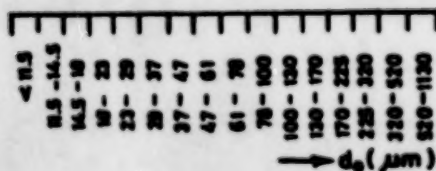
WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.96

$t_m = 6 \text{ min.}$



WEIGHT ON DIODE SIZES
BEST LOG ERROR = 4.92

$t_m = 8 \text{ min.}$



RUN	OIL WEATHERING
C 80	PB _{em}
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
$e = 440 \text{ J/sm}^3$	
GRID OSCILLATION	
$t_{\text{grid}} = 600 \text{ s}$	
TEMPERATURE	
$T = 20 \text{ }^\circ\text{C}$	
SALINITY	
$S = 30 \text{ }^\circ\text{‰}$	
OIL CONCENTRATION	
$C = 50 \text{ ppm}$	

FIGURE III. 54 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



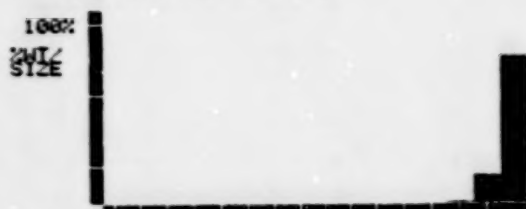
$t_m = 1 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.48



$t_m = 2 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.49



$t_m = 4 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.38



$t_m = 6 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.55



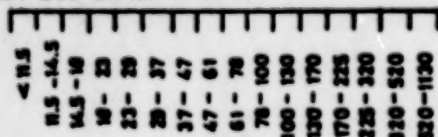
$t_m = 8 \text{ min.}$

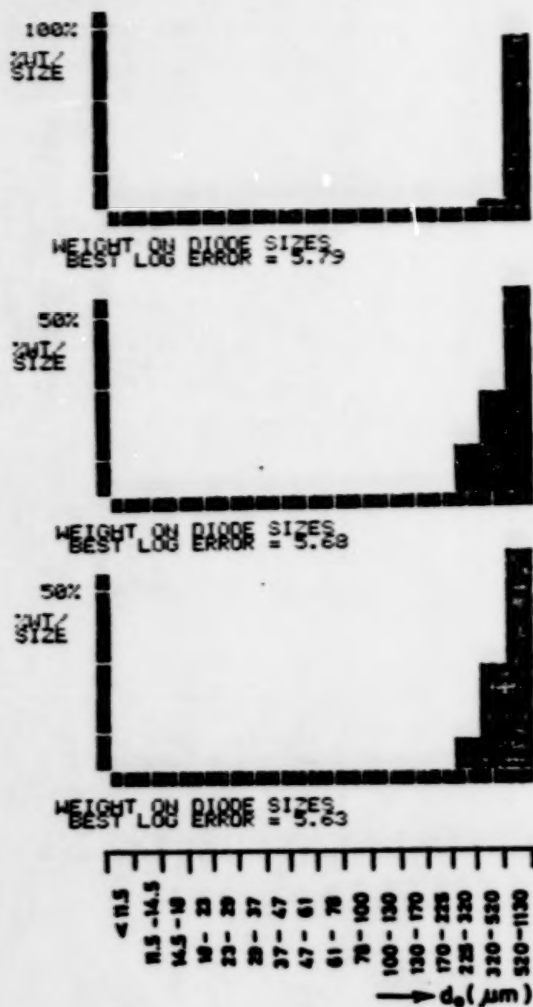
WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.29

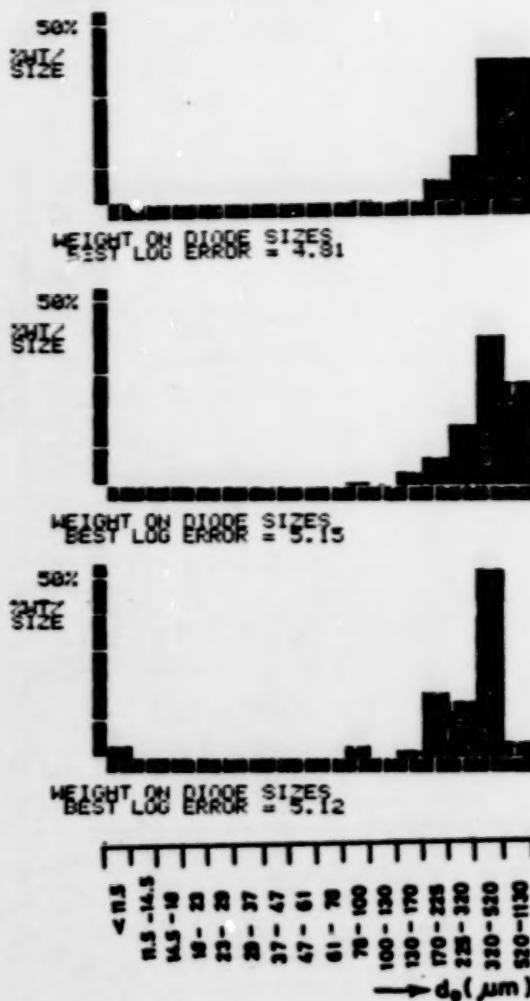


$t_m = 10 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.44







$t_m = 0.5 \text{ min.}$

$t_m = 1 \text{ min.}$

$t_m = 1.5 \text{ min.}$

RUN	OIL, WEATHERING
C 83	PB em
OIL SUPPLY	SUBSURFACE
TURBULENCE LEVEL	$e = 3500 \text{ J/sm}^3$
GRID OSCILLATION	$t_{\text{grid}} = 5 \text{ s}$
TEMPERATURE	$T = 20 \text{ }^\circ\text{C}$
SALINITY	$S = 30 \text{ }^\circ\text{‰}$
OIL CONCENTRATION	$C = 50 \text{ ppm}$

FIGURE III. 57 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA



$t_m = 1 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.12



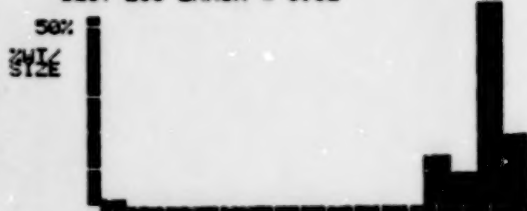
$t_m = 2 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 5.43



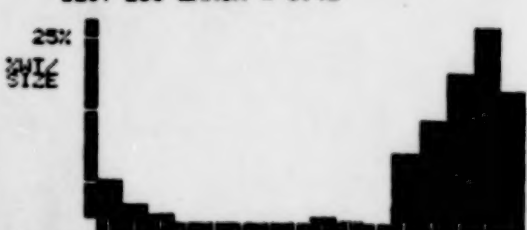
$t_m = 4 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.82



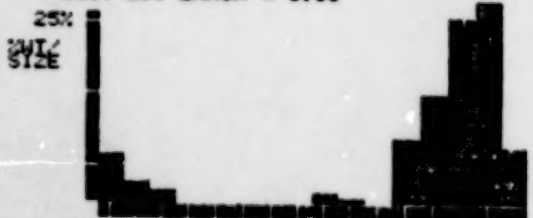
$t_m = 6 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.42



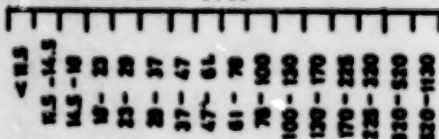
$t_m = 8 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.65



$t_m = 10 \text{ min.}$

WEIGHT ON DIODE SIZES
BEST LOG ERROR = 6.59



RUN	OIL, WEATHERING
C 84	PB _{em}
OIL SUPPLY	
SUBSURFACE	
TURBULENCE LEVEL	
	$e = 3500 \text{ J/sm}^3$
GRID OSCILLATION	
	$t_{\text{grid}} = 600 \text{ s}$
TEMPERATURE	
	$T = 20 \text{ }^\circ\text{C}$
SALINITY	
	$S = 30 \text{ }^\circ\text{‰}$
OIL CONCENTRATION	
	$C = 50 \text{ ppm}$

FIGURE III. 58 DROPLET SIZE DISTRIBUTIONS IN GRID COLUMN
AT TIME t_m . LBPS DATA

III.4 Results

The measurements of the oil droplet size distributions in the grid column consisted of the following data:

- a) LBPS data. The LBPS was equipped with the optical system for particle measurement between 11.5 and 1130 μm . The subranges are shown in Figure III.2. The reliability of the measured droplet size distribution is indicated by the parameter "best log error" (see Figures III.6 through III.58) with the guidelines given in Appendix A.2.1.
- b) video registration.

The following remarks are made concerning the reliability of the droplet size distributions derived from the LBPS and video data:

- a) determination of the largest droplet sizes from the video was reliable if the diameter of the droplets fulfilled $d_o \geq 1000 \mu\text{m}$. Determination took place by direct measurement of the size, or by observation of the terminal velocity.
- b) the determination of complete droplet size distributions (number of droplets per measurable size class) from the video screen was infeasible. The observations were restricted to (1) the determination of the largest droplet size, (2) the determination of an average droplet size (for the size class with the largest volume of oil), and (3) the smallest droplet size (if possible).
- c) measurement of the largest oil droplet from LBPS data was possible only if droplets in the largest subrange of measurements were absent or almost absent (see Figure III.2). Otherwise, the largest droplets were obtained from video.
- d) the minimum droplet size in LBPS measurements was generally not the smallest droplet size present in the water sample. The minimum detectable size class depends on the presence of other classes in the range of measurement. This item is described in Section III.2 and Appendix A.2.1. The Figures A.13a and A.13b show the same droplet size distribution (experiment 55) scanned by the LBPS with the two optical systems applied. The minimum droplet size observed was 100 μm for the

usually applied system, and 20 μm for the other optical system. The Figure A.14 gives examples of the smallest detectable size class for droplet size distributions described by $N(d_0) \sim d_0^{-2.3^*}$ on the size range from infinitely small to different values of the largest size class d_{max} .

- e) in principle, the LBPS data show the droplet size distributions in the range from d_{min} to $d_0 = 1130 \mu\text{m}$. The reliability of the measured distributions depends on the signal/background ratio, where the background level was due to oil droplets from previous experiments, dust particles and air bubbles.
- f) the average droplet size d_{50} , with equal oil volumes for smaller and larger droplets than d_{50} was generally easily observed from the LBPS size distribution. (The example in Figure III.2 leads to $d_{\text{min}} = 50 \mu\text{m}$, $d_{50} = 250 \mu\text{m}$ and $d_{\text{max}} = 800 \mu\text{m}$).

The preceding remarks on the measured data make it clear that the measurements in the grid column did not lead to the complete droplet size distributions in various conditions. However, the main purpose of the present experiments was to obtain the influence of various parameters (oil type, turbulence level, temperature, etcetera) on the droplet size distribution. On the other hand, complete droplet size distributions for a limited number of conditions were measured in the flume experiments described in the Sections V and VI. The influence of the various parameters on the droplet size distributions was observed in the grid column by the influence on the maximum droplet size d_{max} , the average droplet size d_{50} , and the minimum size d_{min} as defined in the preceding remarks. The influence of the parameters on d_{min} , d_{50} and d_{max} defines the influence on the entire droplet distribution. This statement was justified as a result of this study, by the determination of the droplet size distribution $N(d_0) \sim d_0^{-2.3}$ independent from the various parameters.

* The examples in Figure A.14 anticipate on the droplet size distribution relationship determined finally in the present study as the usual distribution in all conditions, see Sections V, VI and VII.

The influence of the water salinity and oil concentration in the water was obtained from the droplet size distributions in Figure III.59:

Figure III.59a: $d_o(f)$ versus water salinity S

Figure III.59b: $d_o(f)$ versus oil concentration C_o .

Other measured droplet size distributions were compiled in the Figures III.60 to III.64, showing graphs with the values of d_{min} , d_{50} or d_{max} versus various parameters:

Figure III.60: d_{min} , d_{50} and d_{max} for Prudhoe Bay crude (PB_o) versus turbulent energy dissipation rate ϵ

Figure III.61: d_{min} , d_{50} and d_{max} for Ekofisk crude (Eko) versus ϵ

Figure III.62a: d_{50} for PB_o versus temperature T

Figure III.62b: d_{50} for Eko versus T

Figure III.63: d_{50} for PB versus weathering state (by evaporation).

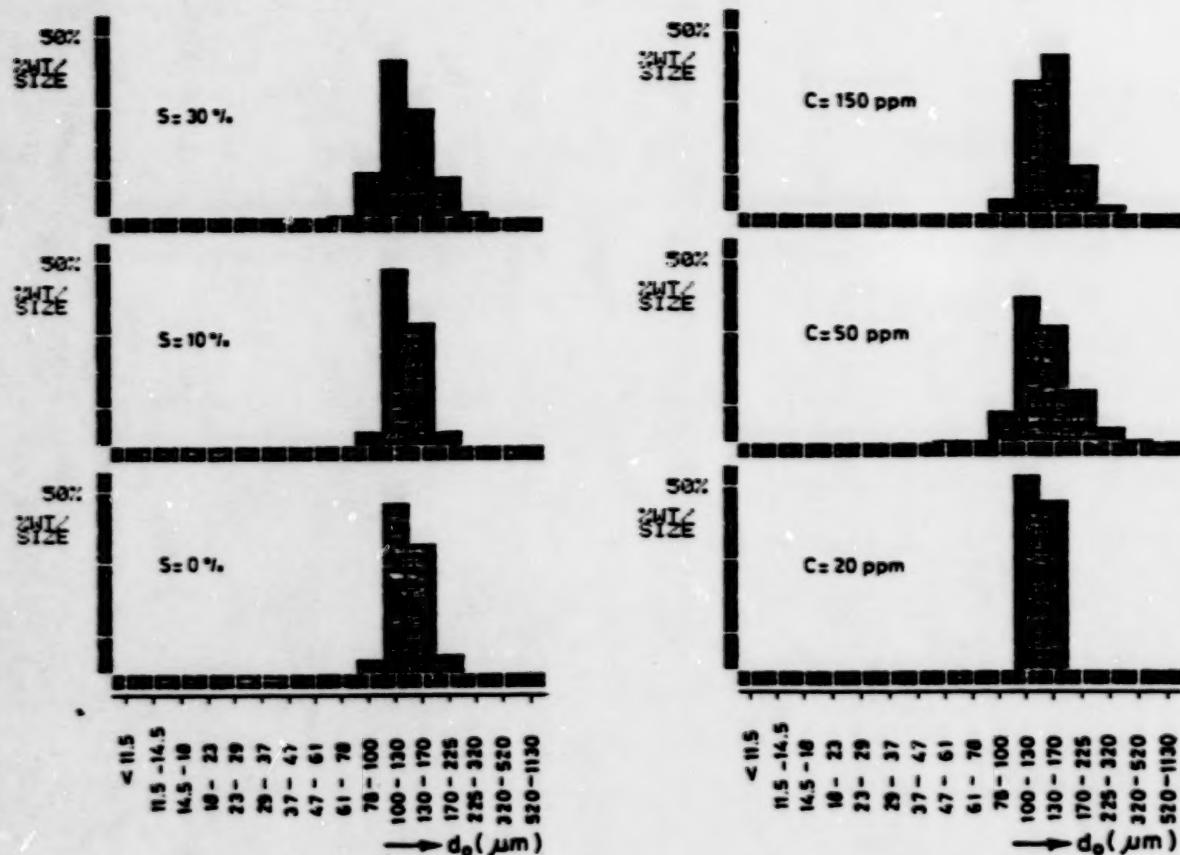
Figure III.64: d_{min} and d_{50} for PB_{em} (emulsified oil) versus ϵ

The following results were obtained visually from the LBPS data and from the reduced data in the Figures III.59 to III.64:

Salinity S . Measurements with $S = 30$ ‰ (salt water), $S = 10$ ‰ (brackish water) and $S = 0$ ‰ (fresh water) were performed. Examples are given in Figure III.59a. The droplet size distribution appeared independent of the salinity.

Concentration C_o . Measurements with oil concentrations $C_o = 20$, 50 and 150 ppm (g/m^3) show similar droplet distributions. Consequently, the effect of the coagulation of oil droplets is not important in this concentration range. Measurement examples are given in Figure III.59b. (The narrow distribution for $C_o = 20$ ppm is apparently due to the low concentration).

Steady state turbulence. A steady state droplet size distribution was observed after about five minutes in a steady state turbulent ambience. The steady state was apparently not an equilibrium between break-up and coagulation (see the preceding results). It is supposed that a changing physico-chemical behaviour of the oil droplets (due to fractionating by, e.g., dissolution or adsorption of components) prohibited further break-up.



a) d_o versus S ($t_m = 8$ min.)

b) d_o versus C_o ($t_m = 4$ min.)

$$PB_0, e = 3500 \text{ J/s m}^3, t_{\text{grid}} = 600 \text{ s}$$

FIGURE III. 59 Droplet size experiments versus water salinity S and oil concentration C_o

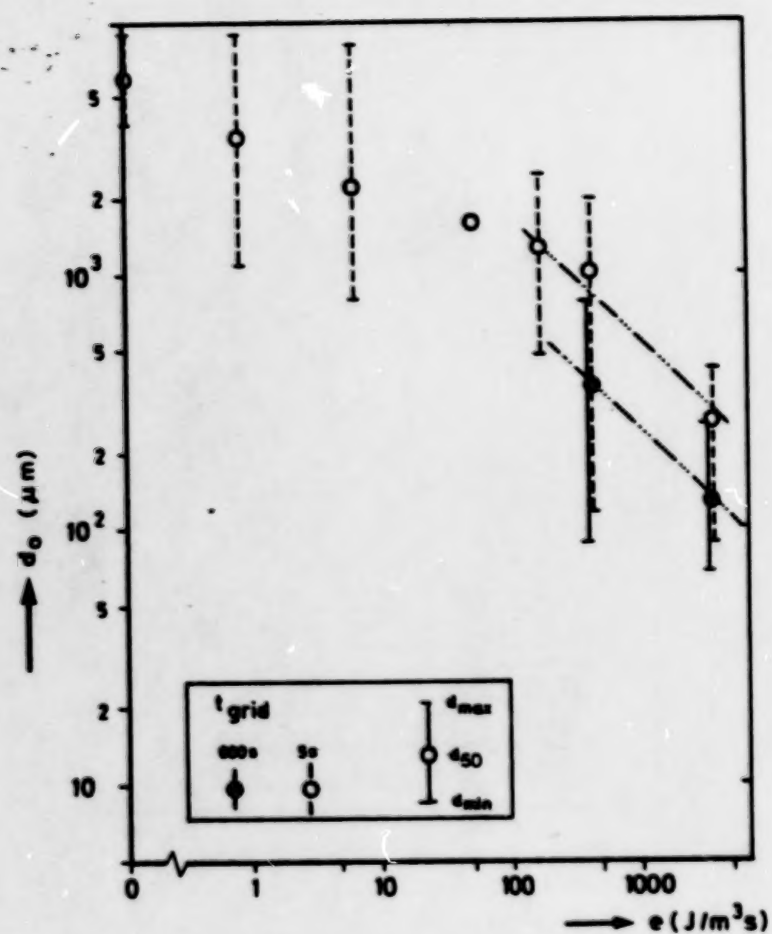


FIGURE III. 60 Droplet sizes for unweathered Prudhoe Bay oil (PB_0) versus turbulent energy dissipation rate e

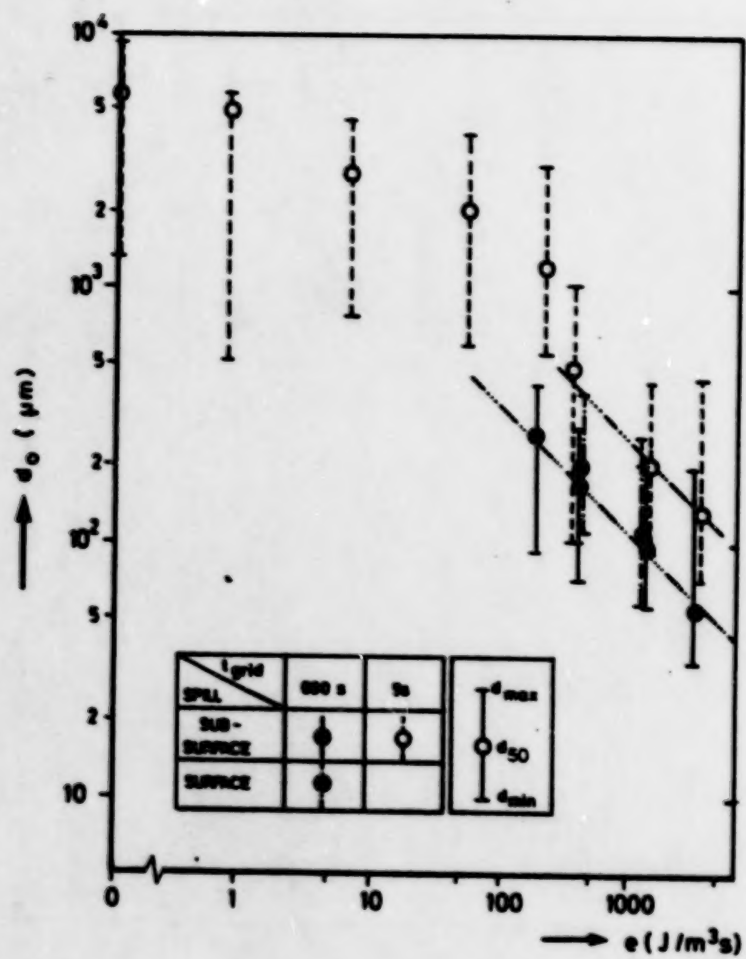


FIGURE III. 61 Droplet sizes for Ekofisk oil (Eko) versus turbulent energy dissipation rate e

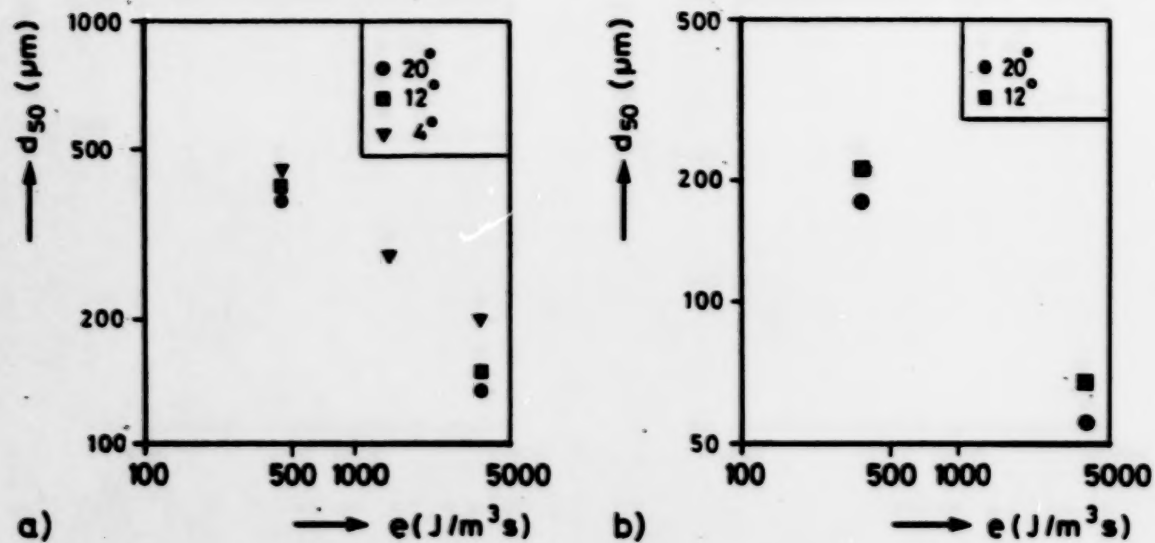


FIGURE III. 62 d_{50} versus turbulent energy e for different temperatures T

a. Prudhoe Bay oil PB_0 ($t_{\text{grid}} = 600$ s)

b. Ekofisk oil Eko ($t_{\text{grid}} = 600$ s)

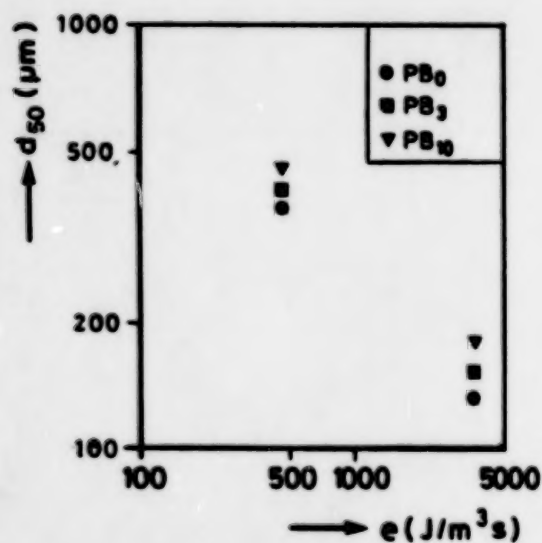


FIGURE III. 63 d_{50} versus turbulent energy e for different weathering states of Prudhoe Bay oil ($t_{\text{grid}} = 600$ s)

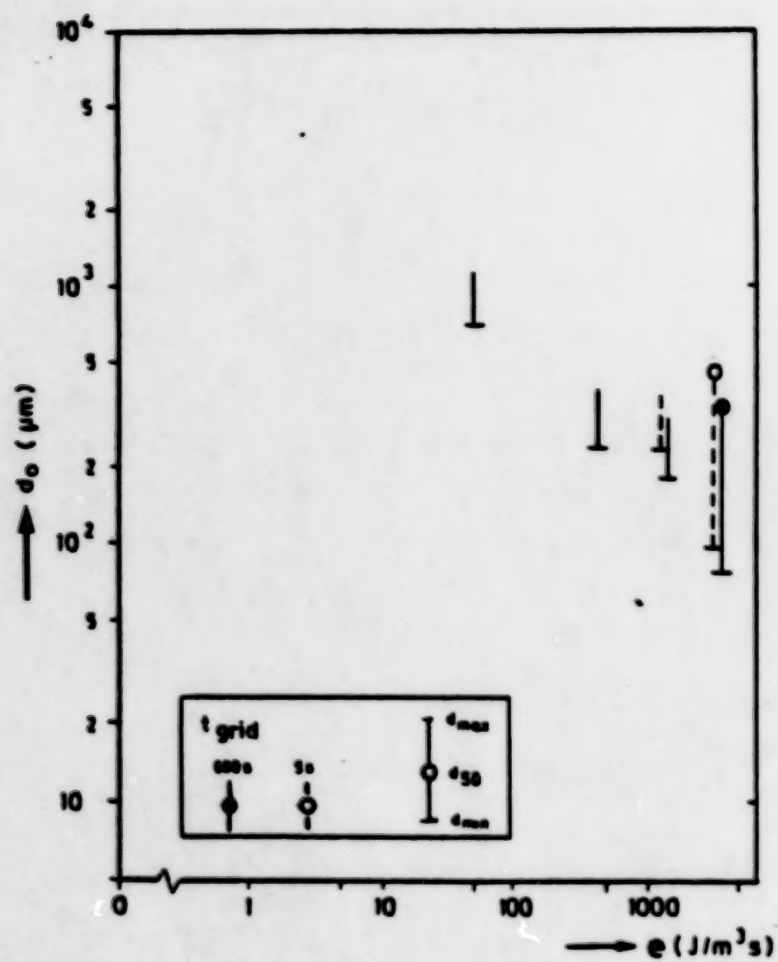


FIGURE III. 64 Droplet sizes for emulsified Prudhoe Bay oil (PB_{em}) versus turbulent energy dissipation rate e

Turbulence level. Measurements on the effects of the turbulence level were plotted in Figure III.60 (Prudhoe Bay crude), Figure III.61 (Ekofisk crude) and Figure III.64 (emulsified PB oil); $d_{\max}$, $d_{\min}$, and d_{50} are shown if available. The figures show the difference in size distribution for $t_{\text{grid}} = 5$ s (simulation of a single breaking wave), and the steady state at $t_m > 300$ s. The droplet sizes of the low-viscosity Ekofisk oil were considerably smaller than the sizes found with Prudhoe Bay oil. The figures suggest a linear relationship between $\log d_0$ (with $d_0 = d_{\max}$, d_{50} or $d_{\min}$) and $\log e$, in the high turbulent energy range from $e = 100 \text{ J/m}^3\text{s}$ to the maximum applied energy $e = 3500 \text{ J/m}^3\text{s}$. This is shown in the Figures III.60 and III.61 by straight lines. All lines appear to have the same slope. This relationship apparently cannot be extended to the low turbulent energy range, with $e < 100 \text{ J/m}^3\text{s}$, probably because in this range the break-up of large oil droplets was due to shear not predominantly generated by turbulence, but with a relatively considerable shear contribution caused by the buoyant oil droplets rising in the ambient water. Clearly, this effect was most significant for low-turbulence water and big oil droplets, when the break-up of droplets was due only to the rise velocity in the experiments in which $e = 0$.

Temperature. The temperature affects oil viscosity and consequently the break-up of droplets. The effect of temperature on the measured droplet size distribution was very clear, Figure III.62 shows the temperature effect on the mean droplets size d_{50} of PB₀ and Ekofisk for different energy levels, e .

Note: The terminal velocity of droplets is affected significantly by temperature due to the influence of the water viscosity on W . However, the data in Figure III.62 were obtained from LBPS measurements during and immediately after the time period of grid oscillation, where the influence of W on the droplet size distribution is small. No data of droplet sizes were obtained from video recordings of terminal velocities.

Weathering state. Figure III.63 shows the $d_{50} - e$ relationship for PB₀, PB₃ and PB₁₀, indicating weathering of Prudhoe Bay oil by evaporation over a period of 0, 3 and 10 days. Weathering increases the viscosity (see

Table A.1) and leads to larger oil droplets.

Emulsification. Figure III.64 shows the measured value of d_{min} and d_{50} versus ϵ for emulsified Prudhoe Bay oil (PB_{em}). The droplet sizes are larger than the droplets of PB_0 , PB_3 and PB_{10} , as could be expected from the high viscosity of the emulsified oil mass. (See Table A.1; PB_{em} has a non-newtonian viscosity behaviour as shown in the shear rate - shear stress curve in Figure A.27).

Surface and subsurface oil. The bulk of the measurements were performed with oil parcels introduced into the column near the bottom. Two experiments were carried out with thin oil films (thickness 50 - 100 μm) on the water surface. Figure III.61 shows almost identical relationships between droplet size and turbulence energy for subsurface and surface oil. (Note that the largest droplet sizes in the size distribution were larger than the thickness of the surface film in contradiction to Aravamudan et al's (1982) assumption on the maximum droplet size).

The experiments indicated that the droplet size distribution depends on turbulent energy, temperature, oil and oil weathering state, the latter three parameters strongly influencing the oil viscosity. Figure III.65 relates the droplet size d_{50} , turbulent energy dissipation rate ϵ , and oil viscosity ν_o . Obviously, the viscosity ν_o is a significant parameter for the $d_o - \epsilon$ relationship.

III.5 Conclusions

The following conclusions were drawn from the grid column experiments on the effect of turbulence on the droplet size distribution of dispersed oil:

- a) Droplet sizes increase with increasing oil viscosity ν_o (see Figure III.65) according to the following relationship:

$$d_o = c_1 \nu_o^{0.34} \epsilon^{-0.50} \quad (III.1)$$

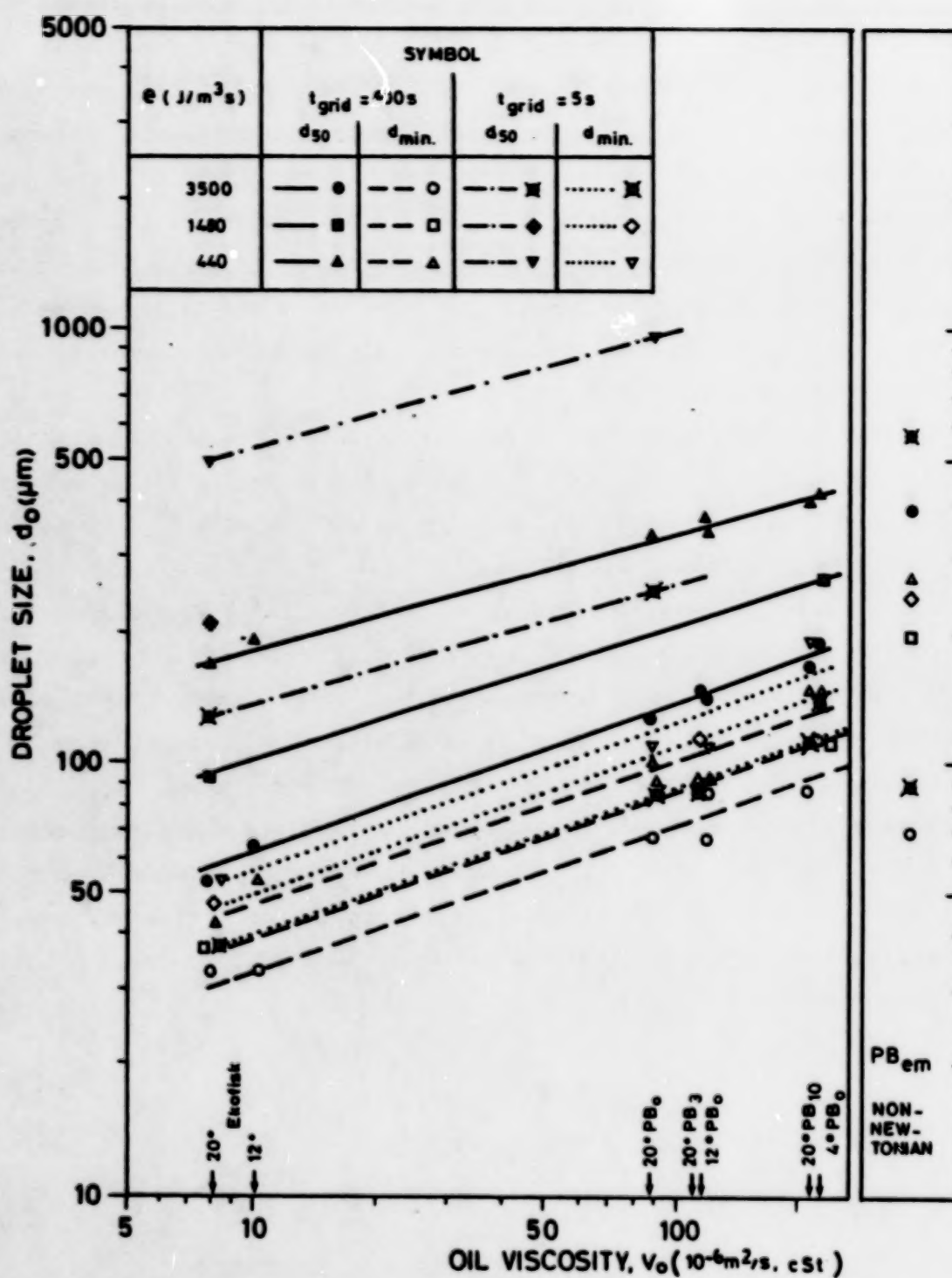


FIGURE III. 65 Droplet sizes versus oil viscosity for experiments in the grid column with different turbulence intensities (e) and time of grid oscillation (t_{grid})

where $d_{\min}$, $d_{\max}$ and d_{50} can be substituted in Equation (III.1). ($d_{\min}$, d_{50} and $d_{\max}$ are defined on pages 119 and 120). Equation (III.1) is valid, at least, in the experimentally applied relatively low-viscosity range, $\nu_0 = 8 \times 10^{-6}$ to $220 \times 10^{-6} \text{ m}^2/\text{s}$ (excluding the high-viscous non-newtonian PB emulsified oil). The viscosity relationship could be supported only from the sufficiently accurate measurements in highly-turbulent ambience ($\epsilon \geq 440 \text{ J/m}^3\text{s}$).

- b) Droplet sizes are independent of oil concentration, water salinity and whether the oil is introduced in the water from a thin oil film on the water surface, or as submerged oil parcels. The droplets depend on oil type, weathering state and temperature only as far as they influence the viscosity (Equation III.1).
- c) Droplet sizes decrease with increasing turbulence, see Figure III.60 and III.61. The d_0 versus ϵ relationship in Equation (III.1) was valid in highly-turbulent water defined by $\epsilon \geq 100 \text{ J/m}^3\text{s}$. $d_{\min}$, d_{50} and $d_{\max}$ can be substituted in Equation (III.1).
- d) Droplet sizes in low-turbulence water ($\epsilon \leq 100 \text{ J/m}^3\text{s}$) are smaller than according to Equation (III.1), because of the additional break-up of big droplets due to the terminal velocity. The shear on the droplets due to the terminal velocity is negligible as compared with the turbulence generated shear in highly-turbulent conditions.
- e) A steady droplet size distribution in steady state turbulence conditions is attained at $t_{\text{grid}} = 5 \text{ min}$. Consequently, the droplet size distribution obtained in breaking waves depends on a time parameter: the proportionality constant c_2 in Equation (III.1) depends on the turbulence duration t_{grid} .

IV. OIL - SPM INTERACTION

IV.1 Introduction

Real ocean conditions imply a certain concentration of suspended particulate matter (SPM) in the water. Typical concentrations are of the order of 0.1 ppm in deep-sea conditions, 1 ppm in coastal zones, up to 100 ppm in surf zones and occasionally even more than 100 ppm in river deltas. Oil droplets may interact with the suspended particles. This chapter describes a series of fundamental oil - SPM interaction experiments in the grid column. The experiments were conducted to investigate the following phenomena:

- a) equilibrium time for the oil - SPM interaction,
- b) oil content of oiled particles,
- c) preference of specific oil droplet sizes in the interaction process,
- d) oil composition in oiled particles, and
- e) flocculation characteristics.

Information about these phenomena was required before laboratory experiments on the diffusion of oiled particles could be performed with modelled hydrodynamic ocean conditions.

The Interim Report [1986] gave the current knowledge on oil - SPM interaction (see also Chapter II). The knowledge is very limited, and consists of the following facts and suppositions important to the present study:

- a) it is supposed by some authors that oil adsorption takes place mainly by adsorption of thin oil films onto silt particles which are subsequently flocculated rather than by adsorption of discrete oil droplets.
- b) electrolytes (salt) in the seawater are important to the destabilization of dispersed oil droplets and suspended silt particles, and to the aggregation of oil droplets and SPM.
- c) oil droplet - SPM interaction requires collisions between the particles. Collisions are due to Brownian motion, velocity gradients generated by currents and turbulence, or differential settling.
- d) oil adsorption depends on the oil composition, SPM composition

(especially the organic carbon content of the particulate matter), and on particle and droplet sizes.

In view of the preceding statements, the oil - SPM interaction experiments in the grid column were conducted to the following parameters:

- a) the salinity of the column water is similar with seawater,
- b) two types of oil (Prudhoe Bay and Ekofisk crude),
- c) two types of silt, one type with a certain organic carbon content (OCC) and the other type with OCC = 0,
- d) varying oil and SPM concentrations,
- e) varying turbulence level and turbulence duration (time of grid oscillation).

IV.2 Suspended Particulate Matter (SPM)

The experiments in the grid column were performed with the following two types of silt:

- a) Kaolinite, obtained from a china factory. The organic carbon content is zero. The particle size distribution was measured with the LBPS supplied with an optical system for particles in the range from 1.2 to 118 μm . The particle size distribution is shown in Figure IV.1. (Flocculation of particles was avoided during the d_g measurements).
- b) Waddensea silt was collected from the intertidal zone of the Wadden Sea along the Northern Dutch coastline. The measured organic carbon content was 7 percent. Figure IV.2 shows the particle size distribution for unflocculated Waddensea silt.

Tests with silt in the saline water ($S = 30 \text{ }^{\circ}/\text{oo}$) of the grid column, without introducing oil, show a pronounced flocculation behaviour for both types of silt. Figure IV.3 shows the floc size distribution for kaolinite in the grid column in three different turbulent conditions with $\epsilon = 55$, 440 and 3500 J/s m^3 . The silt concentration C_g in the column was 10 ppm. The particle size distribution depends on physico-chemical characteristics of the silt and the ambient water. Moreover, the turbulence level influences the floc size, on one hand by the formation of flocs due to col-

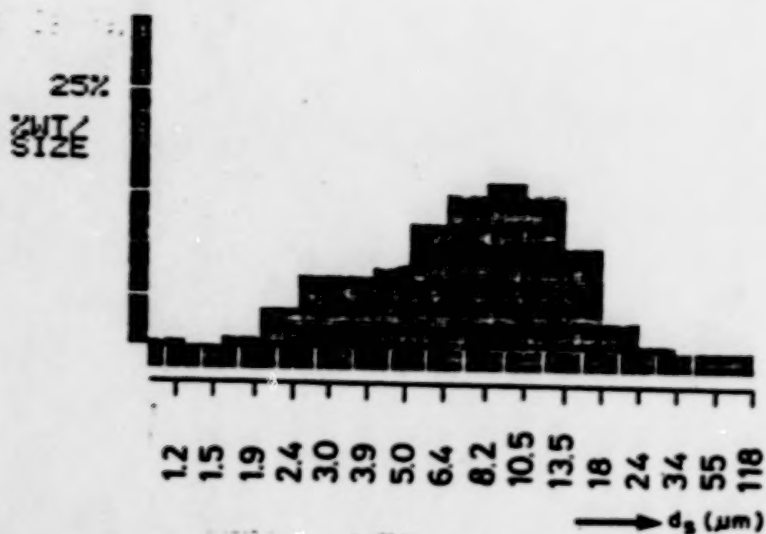


FIGURE IV. 1 Particle size distribution of kaolinite

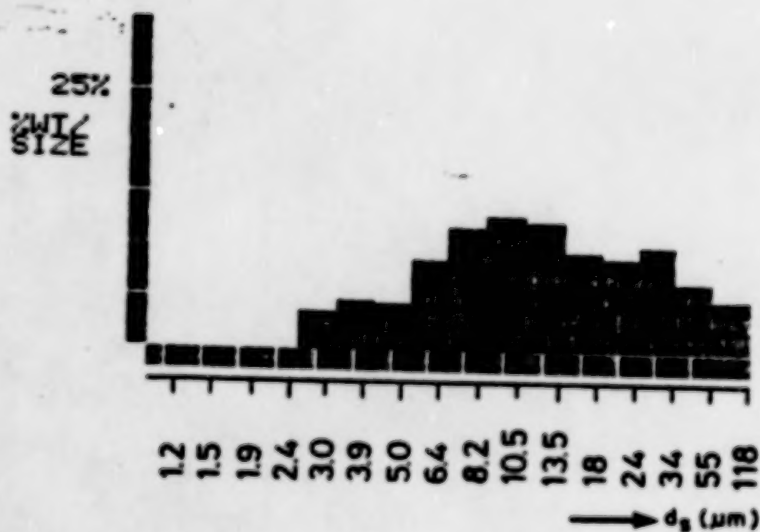


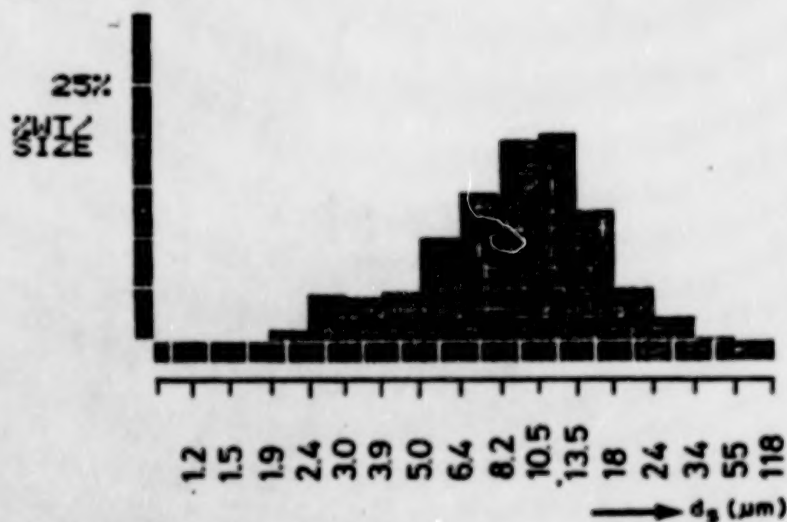
FIGURE IV. 2 Particle size distribution of Waddensea silt



a) $e = 55 \text{ J/m}^3\text{s}$



b) $e = 440 \text{ J/m}^3\text{s}$



c) $e = 3500 \text{ J/m}^3\text{s}$

FIGURE IV. 3 Particle size distribution of flocculated kaolinite
in different turbulent conditions ($C_s = 10 \text{ ppm}$)

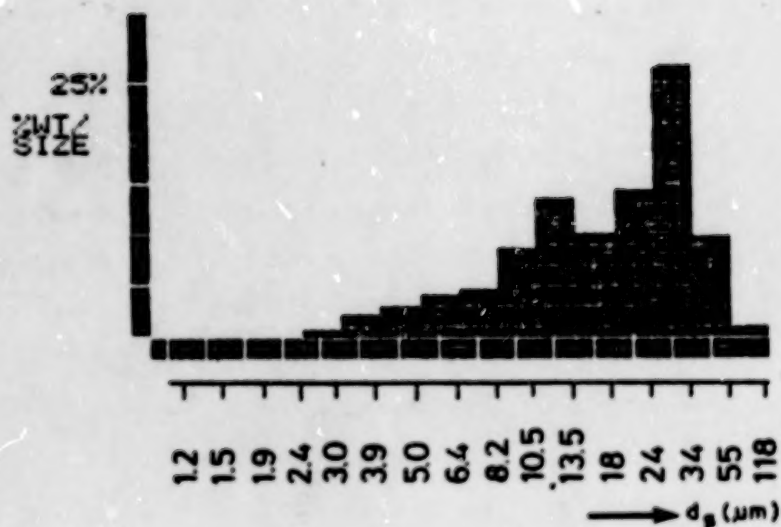


FIGURE IV.4 Particle size distribution of flocculated Waddensea silt in turbulent environment ($\epsilon = 440 \text{ J/s m}^3$, $C_s = 10 \text{ ppm}$).

lisions between the particles, and on the other hand by the break-up of flocs due to shear forces. Figure IV.3 shows an obvious decrease of floc sizes with increasing turbulence level in the range from 55 to 3500 J/s m³. Comparison with Figure IV.1 indicates that there is still some flocculation at $\epsilon = 3500 \text{ J/s m}^3$. Figure IV.4 shows the particle size distribution of Waddensea silt in the grid column in the conditions of $C_s = 10 \text{ ppm}$ and $\epsilon = 440 \text{ J/s m}^3$. The Figures IV.1 to 4 indicate a quite similar particle size distribution for kaolinite and Waddensea silt in unflocculated conditions (Figures IV.1, 2) as well as in flocculated conditions (Figures IV.3a, 4).

IV.3 Experimental Set-up

The oil - SPM interaction experiments were performed in salt water in the grid column. The water salinity S was 30 ‰, and the water density $\rho_w = 1025 \text{ kg/m}^3$. The grid column is very suitable to study the interaction of oil droplets and silt particles in homogeneous conditions of turbulence and oil and SPM concentrations.

An experiment started with the introduction of a certain amount of silt into the column. The silt was mixed homogeneously with the water by forced circulation for fifteen minutes. The silt concentrations applied in the column ranged from $C_s = 6 \text{ ppm (g/m}^3\text{)}$ to $C_s = 75 \text{ ppm}$ in the various experiments. The highest concentration was related to the silt concentration that may occur in the surf zone (see Section IV.1), while the lowest concentration was minimum concentration needed to obtain accurate results in the laboratory measurements as regards the amount of oil and oil composition in an oiled-sediment sample.

Large oil droplets ($d_o = 10 \text{ mm}$) were introduced into the column by the bottom inlet until homogeneous vertical distribution was obtained. (This procedure is similar to the oil droplet size experiments described in Section III). Turbulence was then generated by the oscillating grid during a certain time t_{grid} .

The LBPS was used in the first oil - SPM experiments in the same way as in the droplet size experiments (see Section III). Water samples were withdrawn continuously from the middle of the column and led through the sample cell of the LBPS. The apparatus was equipped with the optical system for measurement of particle sizes in the 1.5 to 118 μm range. The LBPS was not capable of distinguishing oil droplets, SPM particles, flocculated silt and oiled particles. Figures IV.5 gives an example of the size distributions of silt and oil particles in the 1.5 to 118 μm range in a typical experiment. Waddensea silt was introduced and mixed homogeneously in the column, with a concentration $C_s = 15$ ppm. At time $t_m = 0$ the grid was switched on and ran during the entire experiment (3 hours), generating a turbulence level characterized by $\epsilon = 440 \text{ J/s m}^3$. Figure IV.5a ($t_m = 0$ min) shows the silt particle distribution at the start of the experiment. PB₃ oil was introduced at $t_m = 5$ min. ($C_o = 100$ ppm). The particle distribution at $t_m = 7$ min. shows a considerable contribution of oil droplets in the largest measured size range, 55 to 118 μm , while most oil droplets will be larger than 118 μm . (Figure IV.5b). The Figures IV.5c through IV.5h show the temporal trend of the particle distribution due to flocculation. However, these data do not differ from a similar experiment without oil, except, of course, the oil droplet contribution in the 55 to 118 μm size range. The measurable flocculation process appeared similar for experiments with and without oil. Therefore, the LBPS was not used in the bulk of experiments.

The main measurements in the oil - SPM interaction experiments were performed with water samples withdrawn from the middle of the column at different times t_m . Chemical analysis and visual microscopy of the several phases in the samples were conducted.

IV.3.1 Method of chemical analysis

Chemical analysis was performed on oil-SPM water samples by the following procedures (described comprehensively in Appendix A.2.4):

- a) The water samples were poured into 1 litre separatory funnels. (See Figure IV.6a). The funnels were maintained in a stationary position

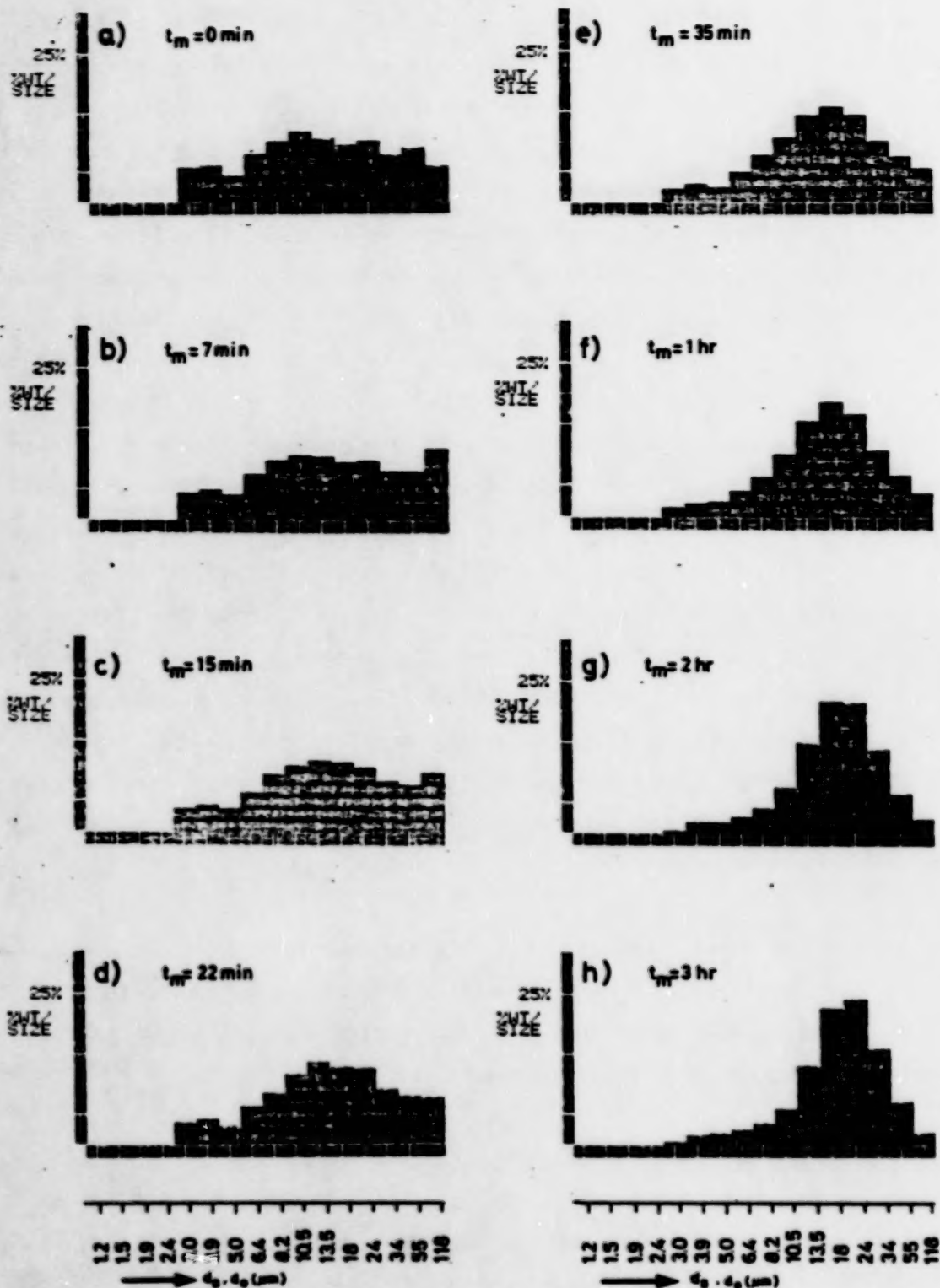


FIGURE IV. 5 Size distributions of SPM and oil droplets in a grid column experiment

for about 20 hours. During that time, the water sample separated into

- a surface layer, phase I, consisting mainly of oil,
- matter still in suspension, phase II, and
- sedimented matter, phase III, consisting mainly of silt.

The different phases were analyzed chemically by a method similar to that applied by SAIC (1986).

- b) In the first two experiments (C88 and C101), the phases II and III together were vacuum-filtered. The oil associated with the silt was recovered and analyzed by flame-induced gaschromatography (FID-GC). The silt on the filter was dried and weighed.
- c) In all subsequent experiments, the phases II and III were analyzed separately because in the previous method the oil on the filter did not consist only of oil adsorbed by SPM, but also contained small oil droplets that were not yet risen to the surface in the 20 hour stationary period. The water samples were collected in small (1 litre) sedimentation columns, as shown in Figure IV.6b. Phase II was withdrawn from the sedimentation column by the nozzle indicated and vacuum filtered, while phase III was collected by a pipette, and vacuum filtered. Further treatment of phase II and phase III was identical, that is, oil recovery by methanol and methylene chloride, and FID-GC analysis.
- d) The filtrate of phase II was analyzed by GC only in a few cases. The dissolved oil concentration was very low and no further attempts were made to analyze this part of phase II.

The grid column samples for GC analysis were generally removed after interaction times of $t_m = 1, 20, 60$ and 180 minutes. During the entire period of 3 hours the grid was oscillating to maintain the turbulence level in the grid column. The interaction time t_m was varied over a wide range to determine the unknown equilibrium oil-SPM interaction time in different circumstances. The minimum time $t_m = 1$ minute and maximum time $t_m = 180$ minutes were experimental limitations. As regards $t_m = 1$, it made no sense to consider an interaction time much shorter than the time of turbulent conditions in the sample bottle during sampling. As regards the maximum time $t_m = 180$ minutes, this is already much longer than the time

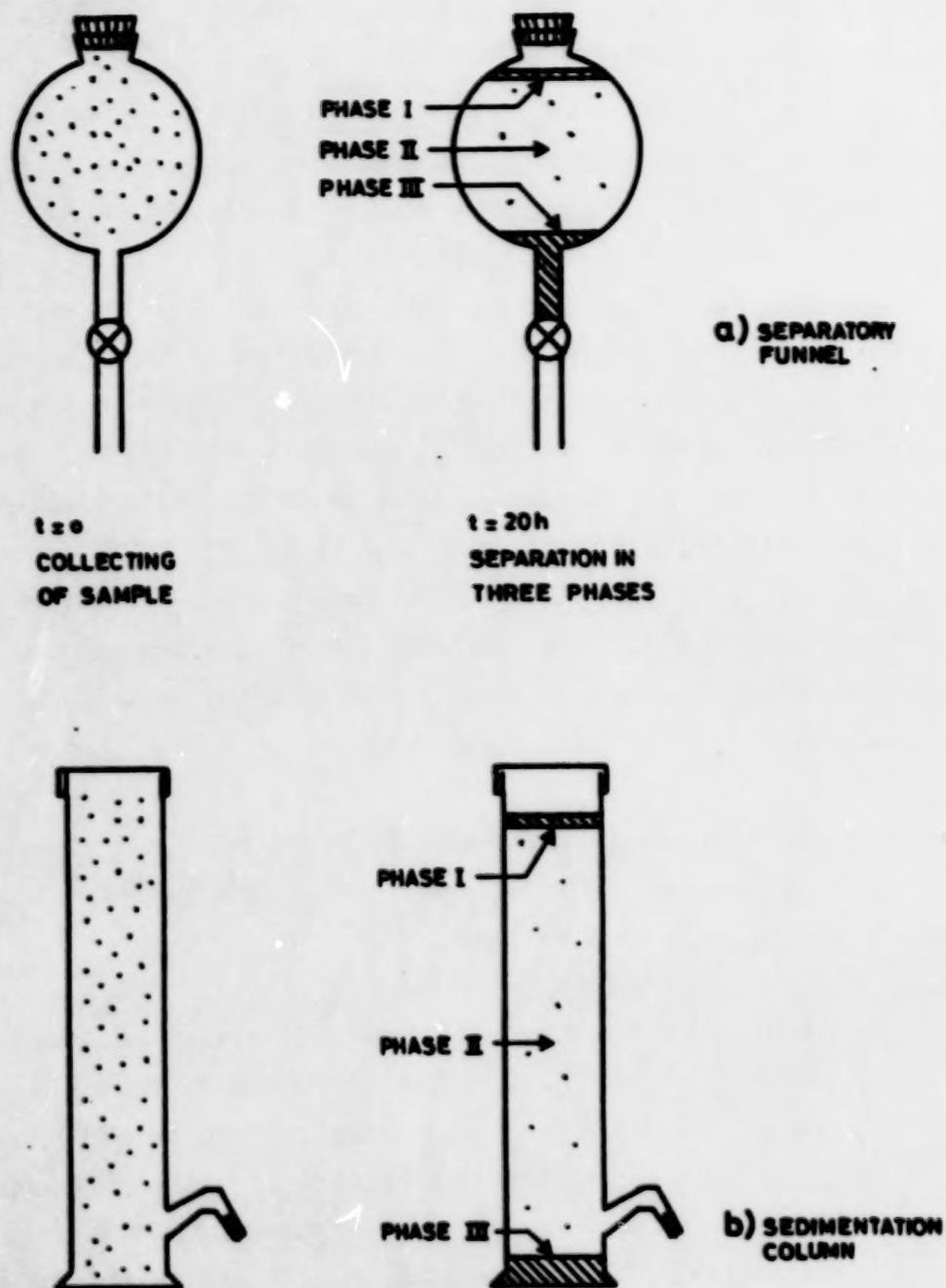


FIGURE IV. 6 Water samples from grid column in separatory funnel and sedimentation column

that flume experiments with simulated ocean conditions for oil-SPM interaction can probably be continued. (The column experiment were considered to be preliminary investigations with regard to flume experiments).

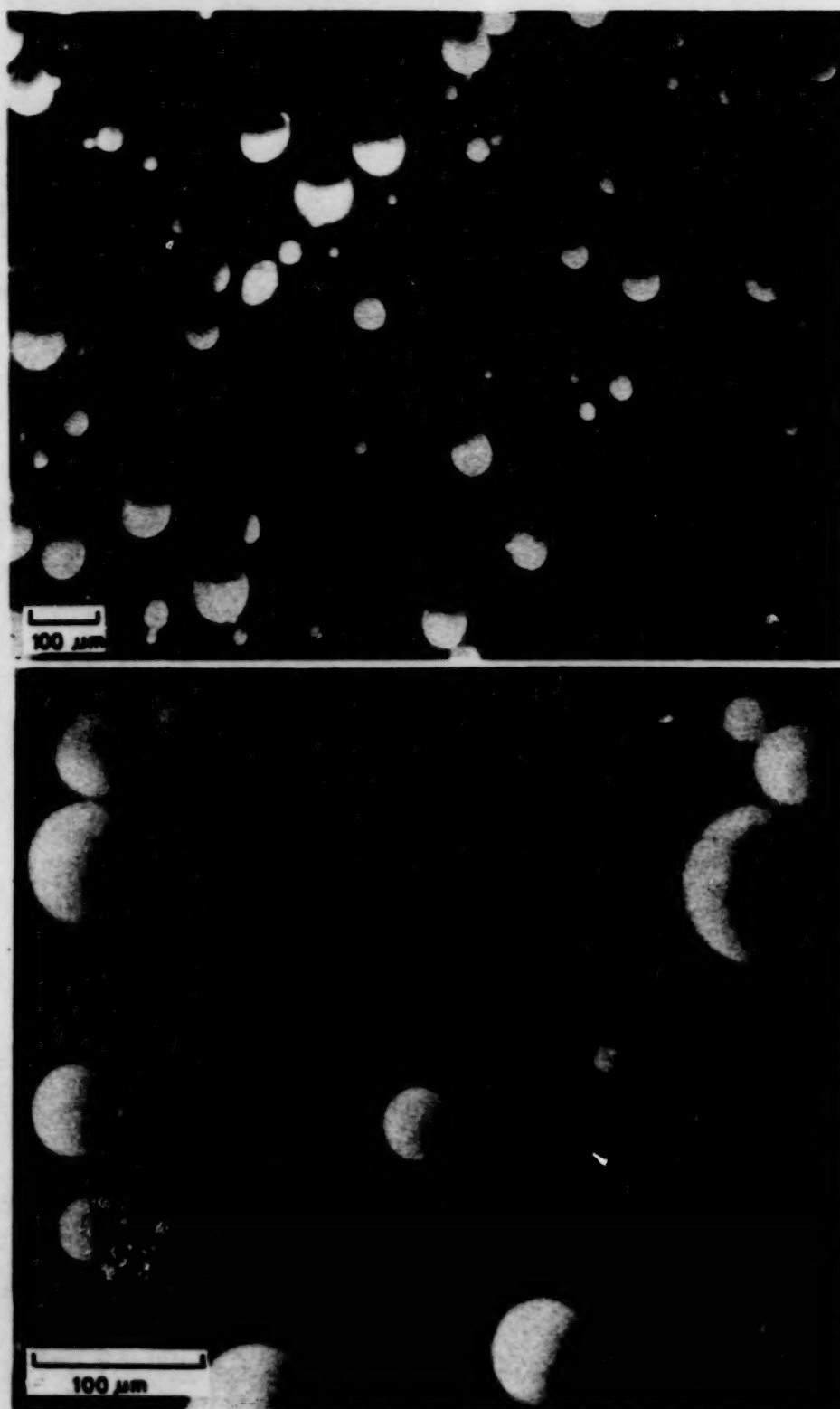
IV.3.2 Method of visual microscopy

Visual microscopy was conducted on water samples withdrawn simultaneously with the samples for GC analysis at interaction times $t_m = 1, 20, 60$ and 180 minutes in the various experiments. The samples were collected in 0.6 litre bottles. Sedimented oiled matter (after a certain stationary period) was observed for all samples, and in many cases buoyant oil droplets were observed as well.

Generally, an ultraviolet light source was used to increase the visibility of the transparent oil droplets and to distinguish the oil droplets from the silt particles by the fluorescent behaviour of oil. (See Appendix A.2.2).

Appendix A.2.2 describes the equipment and the methods used for microscopic observations. It is noted that direct visual observation with the microscope has many more capabilities and gave more information than can be obtained from the microscope photographs presented in this section. The limitations of the photographs are described in Appendix A.2.2. The Figures IV.7 to IV.9 give micrographical examples of the following features:

- a) Pure oil droplets are shown in Figure IV.7. The fluorescent droplets were surfaced to the top glass of the sample cell. The sample was taken during a "blank" experiment without SPM in the grid column.
- b) Figure IV.8 shows SPM-coated buoyant oil droplets, surfaced to the top glass of the cell. The upper subfigure was made with a visible-light source, taken against the light, the lower figure was made with the UV light source (fluorescence).
- c) Oiled sediment on the bottom of the sample cell was photographed using the UV light source, see Figure IV.9.



Run C122 Ekofisk crude

$e = 3500 \text{ J/s m}^3$, $t_m = 10 \text{ min.}$

FIGURE IV.7

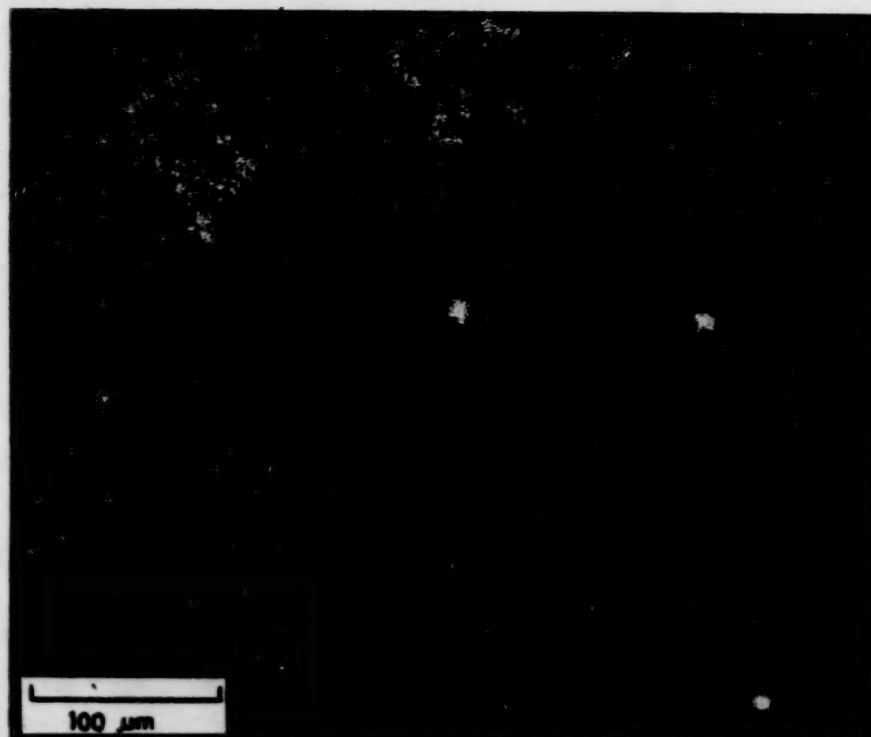
Micrograph of oil droplets in a grid column
experiment

Run C124

PB₃ + kaolinite

$e = 3500 \text{ J/s m}^3$

$t_m = 180 \text{ min.}$



Run C123

Ekofisk + Waddensea

silt

$e = 3500 \text{ J/s m}^3$

$t_m = 180 \text{ min.}$

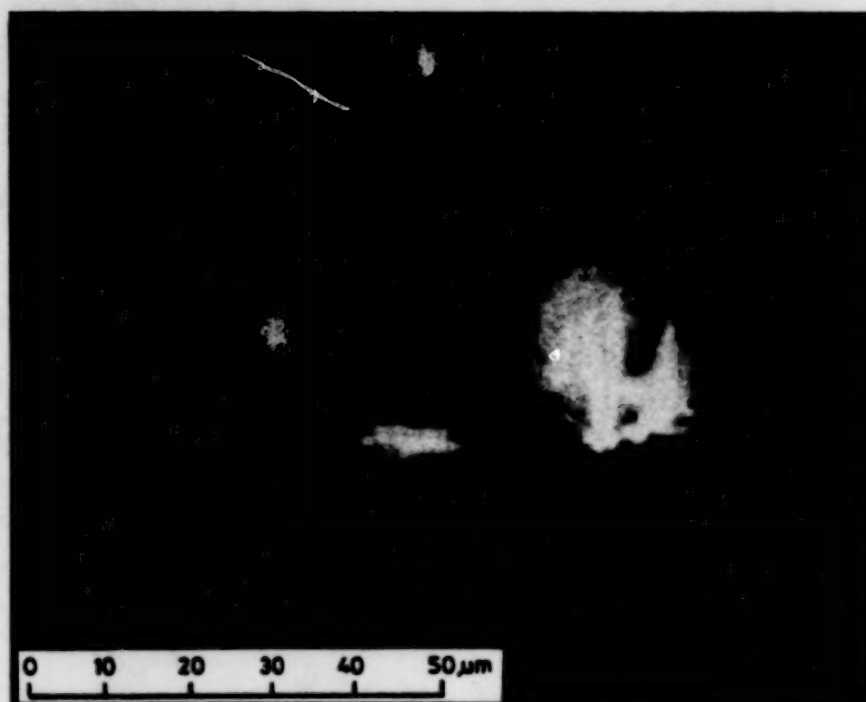


FIGURE IV. 8 Buoyant SPM-coated oil droplets in a grid column experiment



Run C124 PB_3 + kaolinite
 $e = 3500 \text{ J/s m}^3$, $t_m = 180 \text{ min.}$

FIGURE IV.9 Micrograph of oiled sediment from a grid column experiment

IV.4 Presentation of the Measurements

Oil - SPM experiments were performed in the grid column with different values of the following parameters:

- a) oil type: PB_0 = Prudhoe Bay crude, unweathered
 PB_3 = Prudhoe Bay crude, weathered by evaporation for three days
 Eko = Ekofisk crude, unweathered
- b) SPM type: kao = kaolinite, organic carbon content OCC = 0
 wad = Waddensea silt, OCC = 7 %
- c) oil concentration: C_o = 10 35 and 100 g/m³,
- d) SPM concentration: C_{kao} = 6 20 and 60 g/m³,
 C_{wad} = 7.5 15 30 and 75 g/m³,
- e) turbulence level: ϵ = 440 and 3500 J/s m³,
- f) interaction time: t_m = 1 20 60 and 180 minutes.

The experiments performed are listed in Table IV.1, with the experiment number in the first column, and the different parameters in the columns 2 to 7. The data in the columns (8) and (9) deal with the measurements and are discussed in Section IV.5. All experiments except C128 were performed in the grid column.

Experiment C128, consisting of 12 subtests, was performed in small (0.5 litre) beakers. Turbulence was generated by a magnetic stirrer, the energy dissipation rate ϵ is equal in all tests, but the value is unknown. The interaction time in experiment C128 runs from 3 s to 18×10^4 s (= 50 h).

IV.5 Results from Gaschromatographical Analysis

Water samples for GC analysis were removed at t_m = 1, 20, 60 and 180 minutes in almost all experiments. Table IV.2 lists the GC analysis of oil in the various sample phases I, II and III. The total weight of oil in the sample phase is given in column 25. Columns 4 through 24 list the relative n-alkanes from C10 to C30, the concentration of C20 was set to be 100

Table IV.1 Oil - SPM interaction experiments in the grid column

(1) Experiment	(2) Oil type	(3) SPM type	(4) Oil concentration C_o (g/m ³)	(5) SPM concentration C_s (g/m ³)	(6) turbu- lence level ϵ (J/s m ³)	(7) inter- action time t_m (min)	(8) o/s ratio in phase III (λ)	(9) Residual SPM in phase II (g/m ³)
C125	PB ₀	Kao	100	60	3500	$\left\{ \begin{array}{l} 1 \\ 20 \\ 60 \\ 180 \end{array} \right.$	$\left\{ \begin{array}{l} 1.3 \\ 6.3 \\ 4.6 \\ 6.8 \end{array} \right.$	$\left\{ \begin{array}{l} 11.0 \\ 10.2 \\ 9.8 \end{array} \right.$
C126	PB ₀	Kao	35	20	3500	$\left\{ \begin{array}{l} 1 \\ 20 \\ 60 \\ 180 \end{array} \right.$	$\left\{ \begin{array}{l} 2.1 \\ 8.1 \\ 7.9 \\ 7.9 \end{array} \right.$	$\left\{ \begin{array}{l} 4.4 \\ 4.7 \\ 4.8 \end{array} \right.$
C127	PB ₀	Kao	10	6	3500	$\left\{ \begin{array}{l} 1 \\ 20 \\ 60 \\ 180 \end{array} \right.$	$\left\{ \begin{array}{l} 8.0(?) \\ 2.1 \\ 2.6 \\ 2.8 \end{array} \right.$	$\left\{ \begin{array}{l} 3.1 \\ 3.6 \\ 2.7 \end{array} \right.$
C124	PB ₃	Kao	100	60	3500	$\left\{ \begin{array}{l} 1 \\ 20 \\ 60 \\ 180 \end{array} \right.$	$\left\{ \begin{array}{l} 3.2 \\ 11.2 \\ 10.2 \\ 13.5 \end{array} \right.$	$\left\{ \begin{array}{l} 5.4 \\ 4.1 \\ 2.6 \end{array} \right.$
C107	PB ₃	Kao	100	60	440	$\left\{ \begin{array}{l} 1 \\ 20 \\ 60 \\ 180 \end{array} \right.$	$\left\{ \begin{array}{l} 0.3(?) \\ 4.0 \\ 3.9 \\ 3.9 \end{array} \right.$	$\left\{ \begin{array}{l} 11.8 \\ 9.7 \\ 9.9 \end{array} \right.$
C105	PB ₃	Wad	100	7.5	440	$\left\{ \begin{array}{l} 1 \\ 20 \\ 60 \\ 180 \end{array} \right.$	$\left\{ \begin{array}{l} 0.83 \\ 0.90 \\ 1.22 \\ 1.46 \end{array} \right.$	$\left\{ \begin{array}{l} 4.5 \\ 4.5 \\ 4.1 \end{array} \right.$
C88	PB ₃	Wad	100	15	440	$\left\{ \begin{array}{l} 2 \\ 6 \\ 20 \\ 60 \\ 180 \end{array} \right.$	$\left\{ \begin{array}{l} 1.20 \\ 1.66 \\ 1.35 \\ 1.60 \\ 1.31 \end{array} \right.$	
C103	PB ₃	Wad	100	30	440	$\left\{ \begin{array}{l} 1 \\ 20 \\ 50 \\ 180 \end{array} \right.$	$\left\{ \begin{array}{l} \text{no meas.} \\ 0.36 \\ 0.50 \\ 1.36 \end{array} \right.$	$\left\{ \begin{array}{l} 7.7 \\ 6.8 \\ 4.8 \end{array} \right.$
C106	PB ₃	Wad	100	75	440	$\left\{ \begin{array}{l} 1 \\ 20 \\ 60 \\ 180 \end{array} \right.$	$\left\{ \begin{array}{l} 0.20 \\ 0.15 \\ 0.28 \\ 0.50 \end{array} \right.$	$\left\{ \begin{array}{l} 12.2 \\ 11.6 \\ 9.5 \end{array} \right.$

Table IV.1 (continued)

(1) Experi- ment	(2) Oil type	(3) SPM type	(4) Oil concen- tration C_o (g/m ³)	(5) SPM concen- tration C_s (g/m ³)	(6) turbu- lence level ϵ (J/s m ³)	(7) inter- action time t_m (min)	(8) o/s ratio in phase III (%)	(9) Residual SPM in phase II (g/m ³)
C108	Eko	Kao	100	60	440	$\left\{ \begin{array}{l} 1 \\ 20 \\ 60 \\ 180 \end{array} \right.$	$\left\{ \begin{array}{l} 1.9 \\ 3.0 \\ 2.2 \\ 4.0 \end{array} \right.$	$\left\{ \begin{array}{l} 11.5 \\ 10.0 \\ 9.3 \end{array} \right.$
C109	Eko	Kao	100	60	3500	$\left\{ \begin{array}{l} 1 \\ 20 \\ 60 \\ 180 \end{array} \right.$	$\left\{ \begin{array}{l} 5.3 \\ 9.6 \\ 12.1 \\ 12.7 \end{array} \right.$	$\left\{ \begin{array}{l} 7.7 \\ 6.6 \\ 6.1 \end{array} \right.$
C101	Eko	Wad	100	75	440	$\left\{ \begin{array}{l} 1 \\ 20 \\ 60 \\ 180 \end{array} \right.$	$\left\{ \begin{array}{l} \text{no meas.} \\ 1.1 \\ 2.2 \\ 2.3 \end{array} \right.$	
C102	Eko	Wad	100	30	440	$\left\{ \begin{array}{l} 1 \\ 20 \\ 60 \\ 180 \end{array} \right.$	$\left\{ \begin{array}{l} \text{no meas.} \\ 2.2 \\ 2.6 \\ 5.8 \end{array} \right.$	$\left\{ \begin{array}{l} 5.6 \\ 4.2 \\ 3.3 \end{array} \right.$
C123	Eko	Wad	100	30	3500	$\left\{ \begin{array}{l} 1 \\ 20 \\ 60 \\ 180 \end{array} \right.$	$\left\{ \begin{array}{l} 7.8 \\ 18.4 \\ 22.9 \\ 34.0 \end{array} \right.$	$\left\{ \begin{array}{l} 9.5 \\ 6.7 \\ 8.7 \end{array} \right.$
C128A	PB ₃	Kao	100	60	?	$\left\{ \begin{array}{l} 0.03 \\ 0.3 \\ 3 \\ 30 \\ 300 \\ 3000 \end{array} \right.$	$\left\{ \begin{array}{l} 1.1 \\ 1.1 \\ 1.6 \\ 1.2 \\ 11.7 \\ 16.9 \end{array} \right.$	
C128B	Eko	Kao	100	60	?	$\left\{ \begin{array}{l} 0.03 \\ 0.3 \\ 3 \\ 30 \\ 300 \\ 3000 \end{array} \right.$	$\left\{ \begin{array}{l} 0.9 \\ 1.4 \\ 1.6 \\ 4.3 \\ 8.1 \\ 22.8 \end{array} \right.$	

PB = Prudhoe Bay crude

Eko = Ekofisk crude

Kao = kaolinite silt

Wad = Waddensea silt

o/s ratio = oil/SPM weight ratio

Table IV.2 Hydrocarbon concentration in grid column experiments.

(1) (2) (3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)
experiment number phase (see Figure IV.6) T ₀ (calimtas)	Relative n-alkanes concentration (C20 = 100)																					total oil (g)
	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27	C28	C29	C30	
88 -I- 2	75	90	90	100	95		100				100	100		105		105						78.3
88 -I- 6	85	95	95	100	100		105				100	100		100		100						45.9
88 -I- 20	80	90	95	100	100		105				100	100		105		100						13.9
88 -I- 60	80	85	90	95	100		105				100	100		100		100						2.76
88 -I- 100	160	120	100	95	95		105				100	100		105		120						0.92
88 -II-III-2	35?	0	0	0	0		25				100	?		125		145		190		180		0.24
88 -II-III-6	50?	5	5	10	20		60				100	115		130		165		290		320		0.30
88 -II-III-20	85?	10	15	25	40		70				100	120		135		140		240		220		0.22
88 -II-III-60	100?	10	20	30	40		70				100	130		160		200		375		320		0.19
88 -II-III-100	85?	15	25	40	45		75				100	120		135		150		230		255		0.17
101 -I-20	30	50	70	80	90	90	90	95	100	100	100	100	100	105	105	110	105	120	115	110	110	6.49
101 -I-60	35	55	70	85	90	95	90	95	100	100	100	100	100	105	105	110	105	115	115	115	110	5.79
101 -I-100	15	45	70	80	90	90	90	95	100	100	100	105	105	110	110	115						7.58
101 -II-III-20	15	20	35	50	65	75	85	85	90	95	100	105	105	110	120	125	135	130	190	155	185	0.91
101 -II-III-60	10	20	40	55	70	80	85	95	100	100	100	100	105	105	110	115	115	125	140	135	155	1.70
101 -II-III-100	5	5	15	35	55	75	85	90	95	95	100	100	105	110	115	115	115	125	140	130	150	1.54
102 -I-20	45	65	80	90	95	95	90	95	95	100	100	100	100	105	105	105	105	110	110	105	105	14.9
102 -I-60	40	60	80	85	95	95	90	100	95	100	100	100	100	105	105	105	105	110	105	100	105	10.0
102 -I-100	25	55	75	85	95	95	95	100	95	100	100	100	100	105	105	110	105	115	110	100	110	5.0
102 -II-20	35	25	20	50	40	65	65	80	85	90	100	120	140	170	220	280	360	410	700	620	900	0.10
102 -II-60	40	30	35	40	50	60	70	85	90	100	100	115	125	145	170	195	230	205	425	350	480	0.14
102 -II-100	35	30	30	45	50	55	55	60	65	75	100	100	110	130	165	215	220	250	395	385	500	0.08
102 -IIIA-20	40	45	50	55	60	70	80	85	95	100	100	100	105	110	120	125	140	145	175	165	210	0.76
102 -IIIA-60	20	20	25	25	30	30	35	45	70	90	100	105	110	110	120	130	130	135	150	145	180	0.96
102 -IIIA-100	35	50	60	65	75	80	85	90	95	100	100	100	105	110	110	115	120	130	135	120	145	1.89
103 -I-100	10	10	20	40	65	80	90	95	95	100	100	105	95	105	110	110	110	120	125	105	125	0.92
103 -II-20																						0.05-6.10
103 -II-60																						0.05-6.10
103 -II-100	14.	55	35	60	50	105	120	100	100	95	100	120	120	150	280	280	325	415	500	380	440	0.17
103 -IIIA-20	85	45	30	60	40	60	60	70	95	100	105	115	135	175	190	250	250	345	260	360		0.11
103 -IIIA-60	70	50	25	45	30	50	55	70	80	90	100	105	115	120	240	195	230	220	330	285	375	0.15
103 -IIIA-100	65	45	40	50	50	65	75	85	90	100	100	100	105	115	145	145	160	190	195	175	205	0.39

Table IV.2 (continued)

(1) (2) (3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)
experiment number phase (see Figure IV.6) t _m (minutes)	Relative n-alkanes concentration (C20 = 100)																					total oil (mg)
C10 C11 C12 C13 C14 C15 C16 C17 C18 C19 C20 C21 C22 C23 C24 C25 C26 C27 C28 C29 C30																						
105-I-20	40	50	70	80	90	95	95	100	100	100	100	100	95	105	100	100	100	100	100	95	100	7.48
105-I-60	35	35	55	70	85	90	85	95	100	100	100	105	95	105	105	105	105	100	110	100	115	2.32
105-I-180	10	15	15	25	45	70	80	95	95	95	100	100	95	105	110	110	120	120	125			0.28
105-II-20	120	40	40	50	55	70	80	90	90	90	100	120	115	140	175	195	230	230	305	300	395	0.14
105-II-60	100	50	45	45	45	60	65	80	80	85	100	110	120	145	215	225	270	315	415	370	425	0.09
105-II-180	140	20	15	25	30	55	70	80	85	90	100	115	130	165	235	250	305	330	455	440	550	0.08
105-III-1		160?	20	30	35	45	60	125		90	100	125	135	150	235	235	280	325	450	480	540	0.05
105-III-20	90	20	15	25	30	45	60	75	85	90	100	110	120	145	250	220	270	315	355	335	410	0.09
105-III-60	100	40	30	50	50	65	70	85	85	90	100	105	110	130	175	185	220	235	300	300	350	0.14
105-III-180	130	50	30	65	40	65	65	80	80	80	100	115	125	165	225	265	350	365	515	480	560	0.11
106-II-20																						0.04
106-II-60																						0.05
106-II-180																						0.05
106-III-1		250?		175?	20	135?	65	75		80	100	175	155	155	345	300	400	375	730	580	800	0.08
106-III-20	40	45	45	60	55	65	65	80	85	95	100	100	100	115	140	140	165	160	195	165	190	0.42
106-III-60	55	40	45	55	60	65	70	85	85	90	100	105	105	120	145	150	190	175	220	170	225	0.27
106-III-180	75	65	45	70	45	60	60	75	85	90	100	100	115	135	185	195	280	260	375	285	410	0.15
107-I-20	55	75	85	95	100	100	100	100	100	100	100	105	90	100	100	105	100	105	100	95	100	17.5
107-II-20	235	70	30	95	50	80	75	85	85	85	100	140	125	155	240	250	300	375	455	405	500	0.11
107-II-60	?																					
107-II-180	140	55	35	80	60	85	85	90	90	90	100	110	105	110	125	185	215	225	310	290	320	0.14
107-III-1		225?	15	30	30	20	55	65		75	100	135	140	140	260	280	300	315	415	500	465	0.07
107-III-20	80	80	80	90	95	95	95	95	95	100	100	105	90	105	105	110	110	110	110	110	110	2.94
107-III-60	60	65	70	80	90	95	95	95	95	100	100	100	90	100	105	110	105	105	110	105	100	2.70
107-III-180	75	80	80	90	90	95	95	95	95	100	100	100	90	105	105	105	110	110	110	110	105	2.80
108-I-20	70	85	90	95	100	100	100	100	100	100	100	100	100	100	105	100	100	105	105	100	95	32.1
108-II-20	195	30	30	45	50	75	75	90	90	95	100	105	110	115	150	150	160	200	245	265	295	0.28
108-II-60	225	25	20	40	40	60	70	85	90	95	100	105	110	115	140	155	175	200	320	315	370	0.22
108-II-180	560	40	25	60	40	65	65	85	85	85	100	110	115	125	210	230	270	390	465	500	590	0.15

Table IV.2 (continued)

(1) (2) (3)	(4) (5) (6) (7) (8) (9) (10) (11) (12) (13) (14) (15) (16) (17) (18) (19) (20) (21) (22) (23) (24)	(25)
experiment number phase (see Figure IV.6) t _r (minutes)	Relative n-alkanes concentration (C20 = 100)	total oil (mg)
C10 C11 C12 C13 C14 C15 C16 C17 C18 C19 C20 C21 C22 C23 C24 C25 C26 C27 C28 C29 C30		
108-III-1	65 45 70 45 60 60 100 100 100 100 110 115 125 170 195 215 260 320 350 430	0.44
108-III -20	75 60 65 75 85 95 95 95 95 100 100 100 100 105 105 105 105 105 115 110 105	2.08
108-III -60	85 60 65 75 80 90 95 95 100 100 100 100 100 105 110 110 110 125 130 125 125	1.59
108-III -180	90 45 55 70 80 90 95 95 100 100 100 105 100 105 115 115 120 130 155 130 135	0.80
109-I-20	90 95 95 95 95 100 95 95 100 100 100 100 105 105 105 105 105 105 110 100 90	66.8
109-I-60	85 95 95 95 100 100 95 95 100 100 100 100 100 100 100 100 100 105 100 100 95	68.9
109-I-180	75 85 95 95 100 100 95 100 100 100 100 100 100 100 105 100 100 105 100 100 90	59.6
109-II -20	170 30 35 50 60 80 90 95 95 95 100 120 110 110 145 140 140 195 180 205 215	0.63
109-II -60	115 40 45 60 75 85 95 95 95 95 100 110 100 105 125 115 125 150 160 160 175	0.75
109-II -180	120 30 35 60 75 90 95 95 100 100 100 110 105 105 125 120 125 150 150 145 145	0.80
109-III-1	50 65 75 75 80 80 90 95 100 100 100 105 110 120 130 130 150 165 170 180	1.40
109-III -20	65 75 80 90 95 100 95 95 100 100 100 100 105 105 105 100 105 115 105 95	6.6
109-III -60	75 80 85 90 100 100 95 100 100 100 100 100 105 105 105 100 110 105 110 95	7.3
109-III -180	60 75 80 90 100 100 95 100 100 100 100 105 105 110 105 105 105 110 110 90	8.2
123-I-20	85 95 100 100 100 100 95 100 100 100 100 100 105 110 105 105 105 110 110 100 100	83.9
123-I-60	85 95 100 100 100 105 95 100 100 100 100 100 100 105 100 100 100 105 95 95 100	82.3
123-I-180	75 95 95 100 100 105 95 100 100 105 100 105 100 110 100 100 100 105 105 100 100	82.9
123-II -20	45 20 40 70 90 105 105 110 105 105 100 105 100 100 105 100 100 120 110 120 115	1.25
123-II -60	95 45 50 60 65 80 85 90 90 90 100 115 100 105 125 120 125 110 160 155 180	0.83
123-II -180	100 60 65 75 75 85 95 95 100 100 100 115 105 105 115 110 115 105 125 130 140	1.42
123-III-1	40 30 40 40 50 60 80 90 100 100 105 110 115 130 140 150 175 190 220 230	0.62
123-III -20	60 60 70 85 90 100 95 100 100 100 100 100 105 105 105 105 110 105 105 115	5.80
123-III -60	75 75 85 90 95 100 100 100 100 100 100 100 105 105 105 105 105 105 100 105	6.40
123-III -180	50 60 75 80 90 95 95 95 95 100 100 100 105 100 100 105 105 105 100 105	10.00
124-I-20	90 100 105 105 105 105 100 100 100 100 100 100 100 105 100 100 100 100 95 95	65.3
124-I-60	35 80 95 100 100 100 100 100 100 100 100 100 100 100 100 100 100 95 95 95	32.1
124-I-180	45 65 90 95 100 100 100 100 105 100 100 100 100 100 115 100 100 105 105 100 95	14.3
124-II -20	25 25 25 25 45 55 75 80 85 100 125 190 140 270 215 270 240 360 320 380	0.1
124-II -60	30 30 30 30 45 55 75 80 90 100 130 130 140 200 200 240 230 360 315 330	0.1
124-II -180	40 30 40 45 65 70 90 90 95 100 125 125 140 195 180 220 250 290 260 300	0.12
124-III-1	40 25 50 35 45 45 70 80 95 100 105 115 120 140 140 150 170 185 190 175	0.53
124-III -20	120 100 105 105 105 105 105 105 105 105 100 100 100 100 100 95 100 100 95 80	8.2
124-III -60	115 100 105 105 105 105 105 105 105 105 100 100 100 105 100 95 100 100 90 80	7.0
124-III -180	105 95 100 100 105 105 100 105 105 105 100 100 105 105 100 100 100 100 95 85	10.3

Table IV.2 (continued)

(1) (2) (3)	(4) (5) (6) (7) (8) (9) (10) (11) (12) (13) (14) (15) (16) (17) (18) (19) (20) (21) (22) (23) (24)	(25)																						
experiment number phase (see Fig. IV.6) t_m (minutes)	Relative n-alkanes concentration (C20 = 100)																							total oil (mg)
	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27	C28	C29	C30			
125-I-20	75	85	95	100	105	105	105	100	100	100	100	100	100	100	100	100	100	100	100	100	95	65.4		
125-I-60	65	80	85	95	105	100	100	100	100	100	100	100	95	100	100	95	100	100	95	105	90	40.2		
125-I-180	45	65	80	85	100	95	100	100	100	100	100	100	100	100	100	100	100	100	105	110	85	22.3		
125-II-20	35	25	30	35	65	60	60	80	85	90	100	105	105	110	130	125	145	160	170	175	170	0.4		
125-II-60		30	40	45	60	75	90	90	90	95	100	100	100	105	115	115	125	130	140	140	140	1.7		
125-II-180	30	20	20	30	70	70	85	90	95	100	100	105	100	100	125	110	130	140	145	145	145	0.35		
125-III-1		55	55	55	55	60	65	90	95	100	100	110	110	110	145	150	160	170	195	200	220	0.18		
125-III-20	50	70	80	90	95	95	95	90	95	100	100	105	100	100	100	100	100	100	105	100	105	4.35		
125-III-60	100	70	80	85	90	95	95	95	95	100	100	105	100	105	105	100	100	100	100	100	105	3.10		
125-III-180	110	85	90	95	100	100	100	100	100	100	100	100	100	100	100	100	95	100	100	100	100	4.60		
126-I-20	65	75	90	95	100	100	100	100	100	100	100	105	105	105	105	100	105	100	105	100	105	22.00		
126-I-60	75	85	100	105	105	100	100	100	100	105	100	100	105	105	100	100	105	105	105	100	105	18.00		
126-I-180	55	65	85	90	95	95	95	95	95	100	100	105	105	105	100	100	105	105	115	105	110	8.50		
126-II-20		40	30	40	30	60	60	60	80	85	100	110	125	130	220	185	200	185	295	320	340	0.15		
126-II-60		50	50	55	55	75	75	75	85	90	100	110	110	110	205	160	180	145	240	235	235	0.15		
126-II-180		40	45	55	60	75	75	75	85	95	100	120	105	100	120	105	115	125	140	130	140	0.40		
126-III-1		170?		130?	20	105?	40	105	90	90	100	150	170	210	380	390	475	475	685	550	620	0.08		
126-III-20		55	70	75	80	85	85	85	90	100	100	100	100	100	105	105	105	100	110	105	110	1.65		
126-III-60		70	80	85	90	90	90	90	90	100	100	105	105	105	105	105	110	110	110	110	110	1.85		
126-III-180		60	70	80	85	90	90	95	95	100	100	105	105	100	105	105	105	105	110	105	110	1.85		
127-I-20		50	25	40	55	60	75	85	90	95	100	100	100	110	110	125	125	130	135	145	145	170	2.15	
127-I-60		20	20	15	15	15	25	25		90	100	100	110	110	140	160	170	200	245	280		0.25		
127-I-180																								
127-II-20		60	70	70	65	120	130	170	145	120	100	95	120	130	235	220	240	365	390	350	390	0.35		
127-II-60			35	115	45	100	75	115	100	90	100	160	130	110	185	245	312	240	400	380	390	0.16		
127-II-180		95?	20	90	30	80	65	105	100	95	100	140	130	135	215	205	225	235	335	355	440	0.14		
127-III-1		30		30		40	55	140		95	100	145	150	170	290	300	375	375	705	570		0.04		
127-III-20		120?	20	100	30	75	50	95	90	90	100	130	135	145	240	245	300	375	455	445	600	0.1		
127-III-60		150?	40	110	35	85	55	95	90	85	100	220	130	130	325	270	310	300	405	440	600	0.13		
127-III-180		100?	30	90	40	75	50	90	90	90	100	140	140	140	240	240	275	350	425	445	560	0.14		
128-1		75	15	75	75	80	60	80	90	95	100	110	120	125	180	190	195	255	340	325	320	0.16		
128-2		80?	20	75	80	85	65	80	90	95	100	110	115	115	180	180	195	225	310	300	325	0.17		
128-3		85	90	85	90	100	90	85	95	100	100	120	105	100	170	140	150	210	230	210	235	0.23		
128-4		85	85	80	85	95	90	85	90	100	100	120	110	115	190	170	190	260	300	300	310	0.17		
128-5		70	75	85	95	90	80	70	90	100	100	100	100	100	105	105	100	105	115	110	105	3.12		
128-6		65	75	90	90	90	80	70	90	100	100	105	100	105	105	110	105	110	120	115	115	3.64		
128-7		50	30	60	65	75	65	100	100	100	100	115	100	105	170	175	195	265	295	315	330	0.19		
128-8		40	20	45	60	75	80	110	105	100	100	115	105	110	160	170	190	260	315	360	410	0.20		
128-9		55	40	60	50	80	90	105	105	105	100	105	100	105	130	140	140	170	195	200	225	0.28		
128-10		35	35	50	55	75	90	100	100	100	100	105	100	100	130	140	160	205	225	215	220	0.74		
128-11		55	65	80	85	85	90	95	100	100	100	100	100	100	100	100	105	105	105	95	90	2.71		
128-12		55	60	70	75	80	85	95	100	100	100	100	100	100	105	110	105	115	110	115	100	1.42		

(column 14).

The oil - SPM weight ratio, o/s, of sedimented matter (phase III) in the sedimentation column, is given in Table IV.1, column (8). The weight of SPM still in suspension after a long time in stationary position, phase II, is given in Table IV.1, column (9).

The total set of experiments yields the following comparative analysis:

- a) experiment C125, C126, C127. Derivation of the effect of oil and SPM concentration with constant oil/SPM proportions. Figure IV.10 shows the measured o/s ratio in phase III (non-buoyant oil-SPM agglomerations).
- b) experiments C105, C88, C103, C106. Experiments with different Waddensea silt concentrations but equal PB₃ oil concentrations (Figure IV.11a).
experiments C101 and C102 with different Waddensea silt concentration but equal Ekofisk oil concentrations (Figure IV.11b).
- c) experiments C125, C124, C109, C107, C108. Comparison of kaolinite experiments with different oil types PB₀, PB₃ and Ekofisk (Figure IV.12a).
experiments C106, C101. Comparison of Waddensea silt experiments with different oil types PB₃ and Ekofisk (Figure IV.12b).
- d) experiments C106 and C107 with PB₃ and different SPM types (Figure IV.13a)
experiments C101 and C108 with Ekofisk and different SPM types (Figure IV.13b).
- e) experiments C107, C124: PB₃ + kaolinite (Figure IV.14a)
experiments C108, C109: Ekofisk + kaolinite (Figure IV.14b)
experiments C102, C123: Ekofisk + Waddensea silt (Figure IV.14c)
} sets of experiments with different turbulent energy
- f) experiments C128A, C128B. Experiments with kaolinite and different oil types in stirred beaker. (Figure IV.15).
} sets of experiments in different laboratory facilities

- | | | |
|--|---|---|
| <p>g) experiments C124, C107, C128A:
PB₃ + kaolinite. (Figure IV.16c)</p> <p>h) experiments C108, C109, C128B:
Ekofisk + kaolinite (Figure IV.16)</p> | } | <p>(grid column and stirred beaker), and with different turbulent energy.</p> |
|--|---|---|

The following conclusions were drawn:

- a) A steady state o/s ratio was reached within 20 minutes for experiments with kaolinite, (see Figures IV.10, IV.12, IV.14a,b). It is well-known that the oil-SPM interaction depends on the droplet size distribution $d_o(f)$ and it is known from the droplet size experiments that it took about 5 minutes to find a steady $d_o(f)$ (Section III). The kaolinite experiments indicated oil-SPM interaction times of the same order of magnitude or smaller than $t_m = 5$ minutes to obtain a steady value of $d_o(f)$.

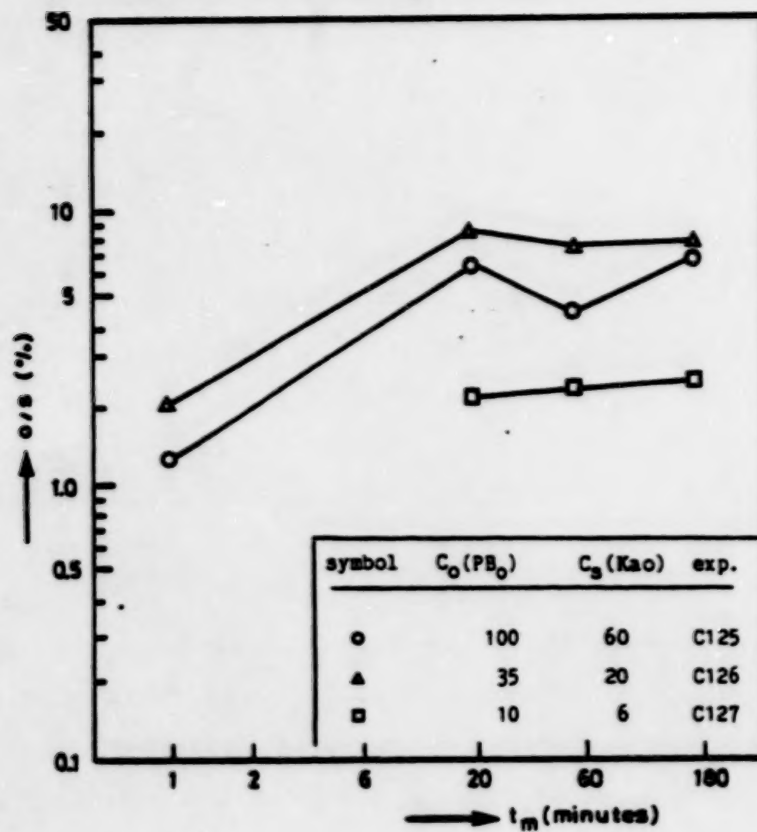
On the other hand, the o/s ratio increased with all applied interaction times ($t_m = 1, 20, 60$ and 180 minutes) for the experiments with Waddensea silt, see the Figures IV.11a,b and IV.14c. This conclusion was valid for all experiments conducted, that is, experiments with PB₀, PB₃, Ekofisk, and turbulence levels with $e = 440$ and $e = 3500$ J/s m³. The Waddensea silt experiments indicated long oil-SPM interaction times, relative to the time to obtain a steady oil droplet distribution.

Discussion. Two processes might be involved in the obtaining of a steady state:

The first process concerns the turbulence causing collisions and subsequent coalescence or agglomeration of the particles and on the other hand causing break-up of droplets and agglomerates due to shear. A steady state means an equilibrium between coalescence/agglomeration and break-up.

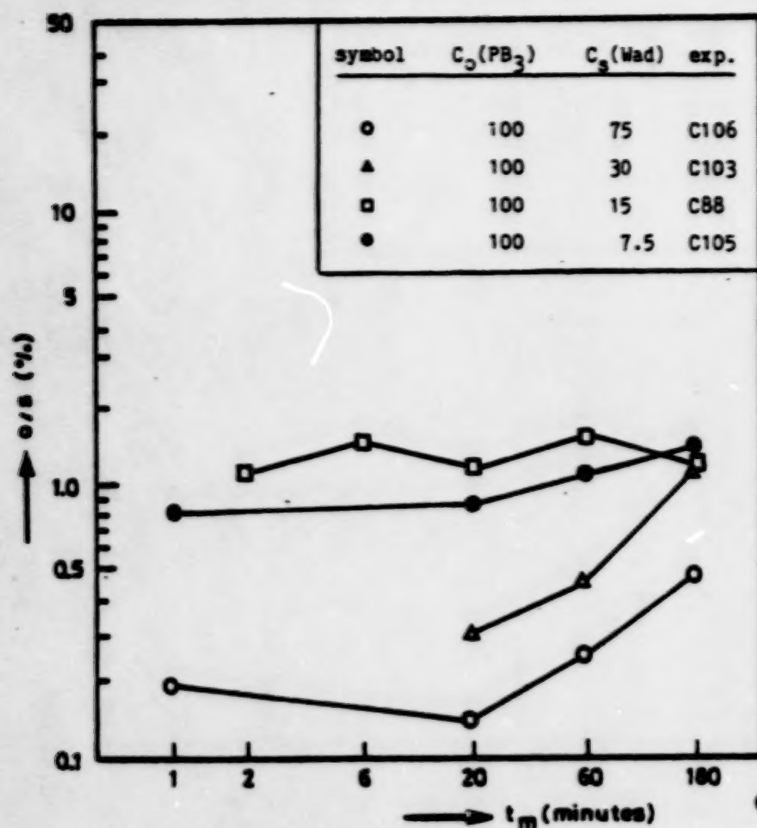
The second process concerns the fractionating of oil (for instance, by dissolution of soluble oil components) and subsequent changing oil-SPM interaction.

In similar conditions, the steady state o/s ratio was obtained earlier

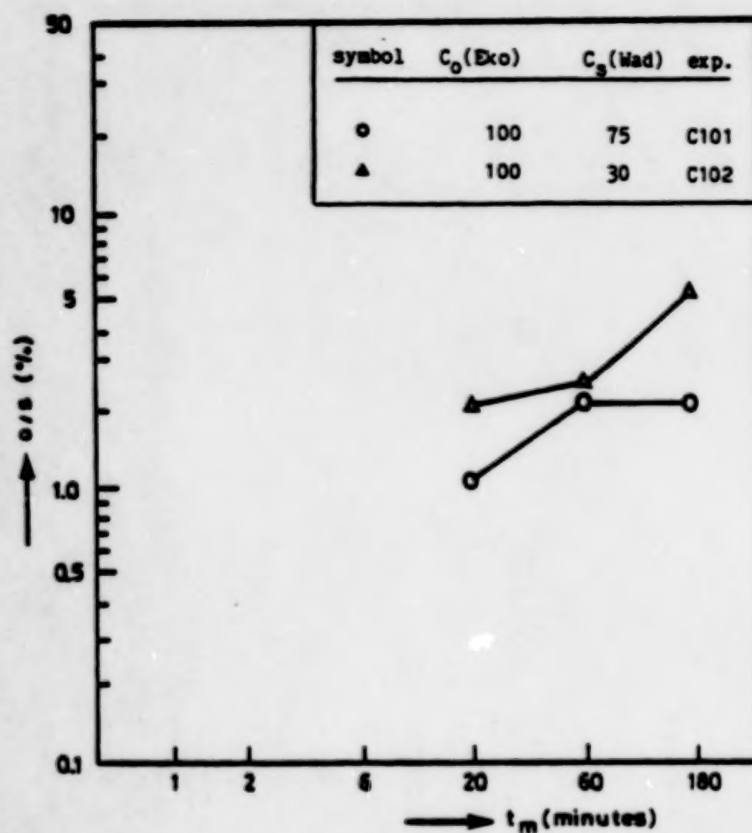


$PB_o + \text{kaolinite}$
 $e = 3500 \text{ J/s m}^3$

Composition of non-buoyant oil-SPM agglomerates over time.
FIGURE IV.10 Experiments with varying oil and SPM concentrations but
 constant concentration ratios



a) PB_3 + Waddensea silt
 $e = 440 \text{ J/s m}^3$



b) Ekofisk + Waddensea silt
 $e = 440 \text{ J/s m}^3$

FIGURE IV.11 Composition of non-buoyant oil-SPM agglomerates over time.
 Experiments with varying SPM concentrations

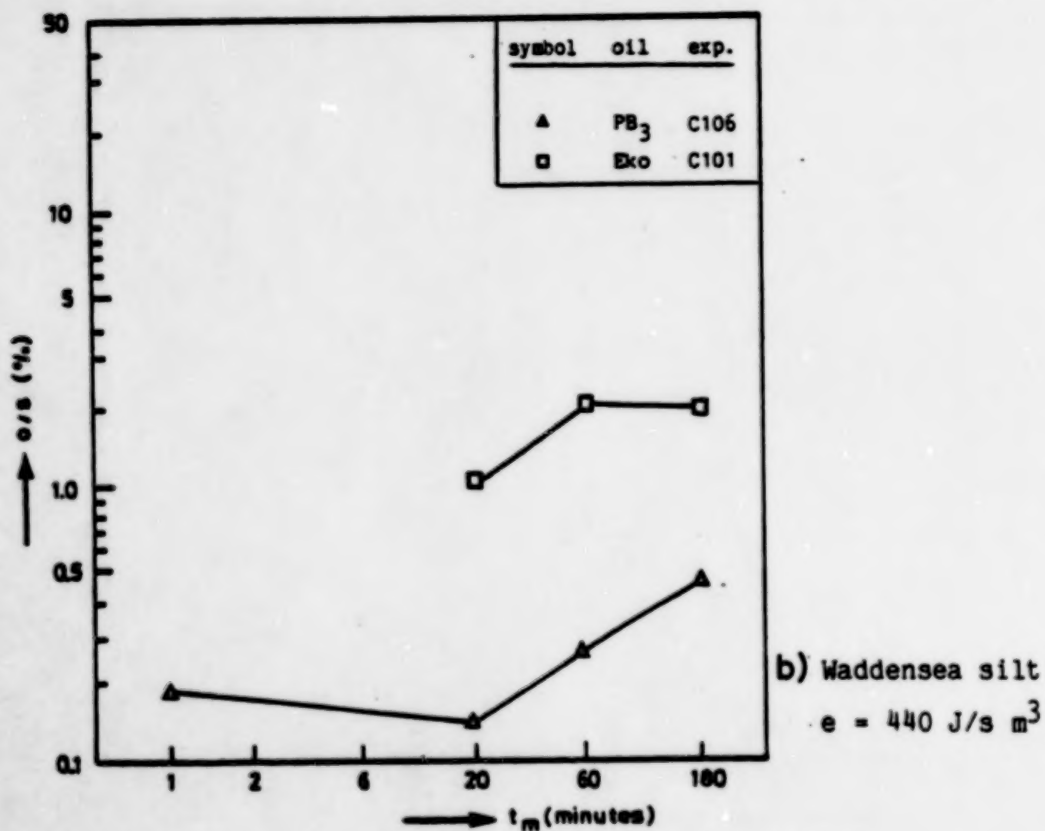
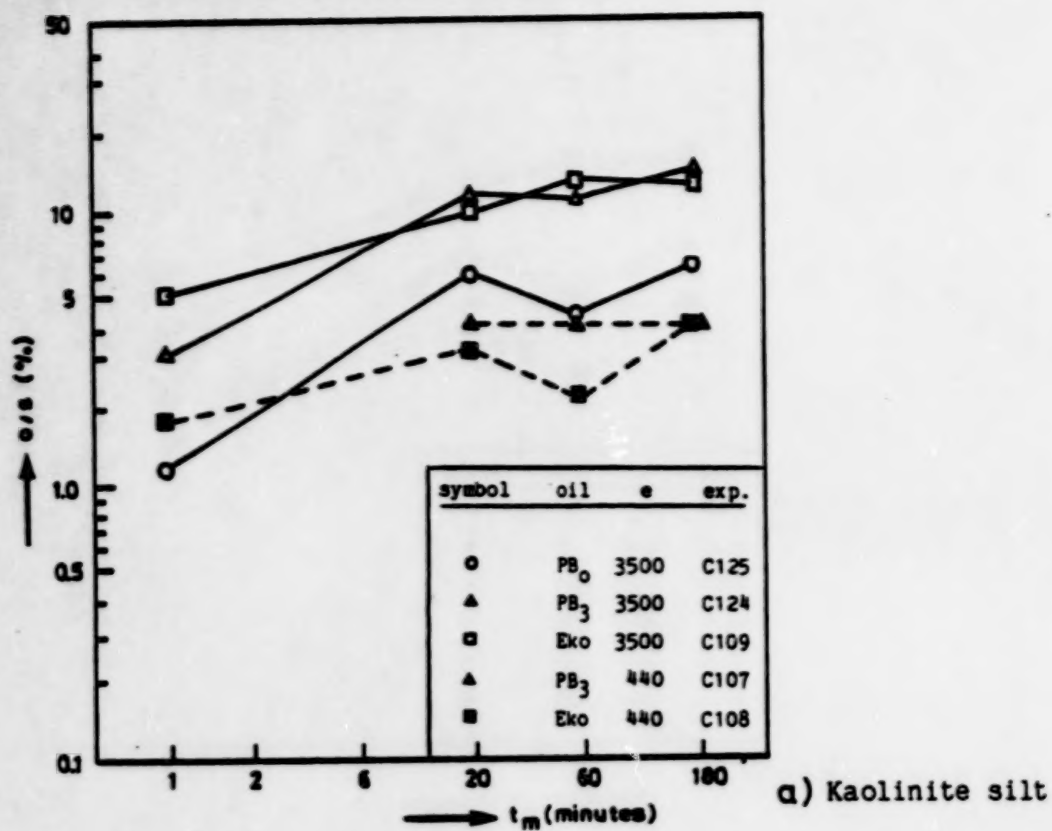
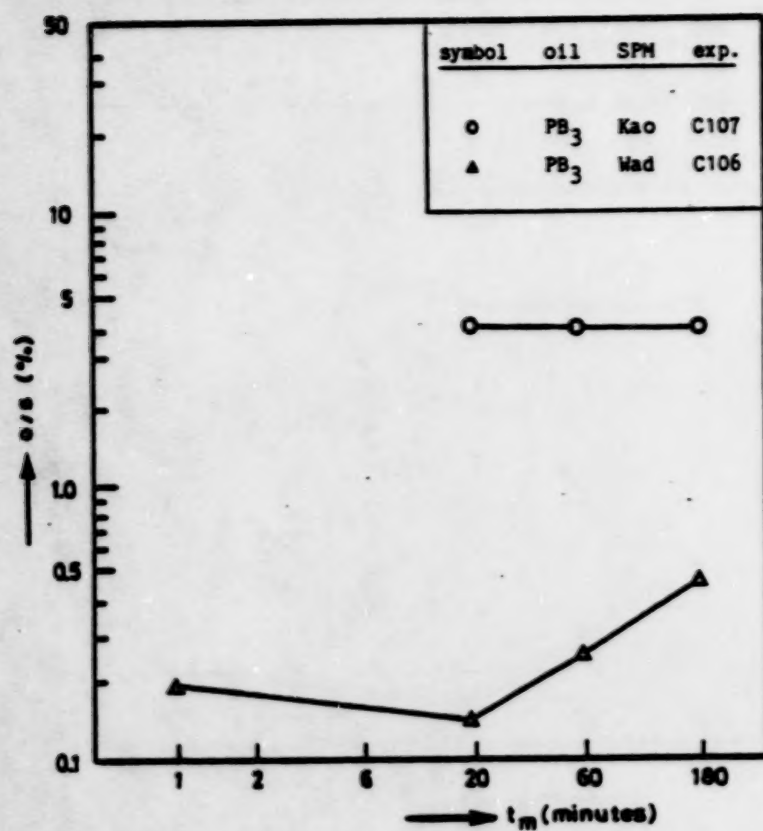
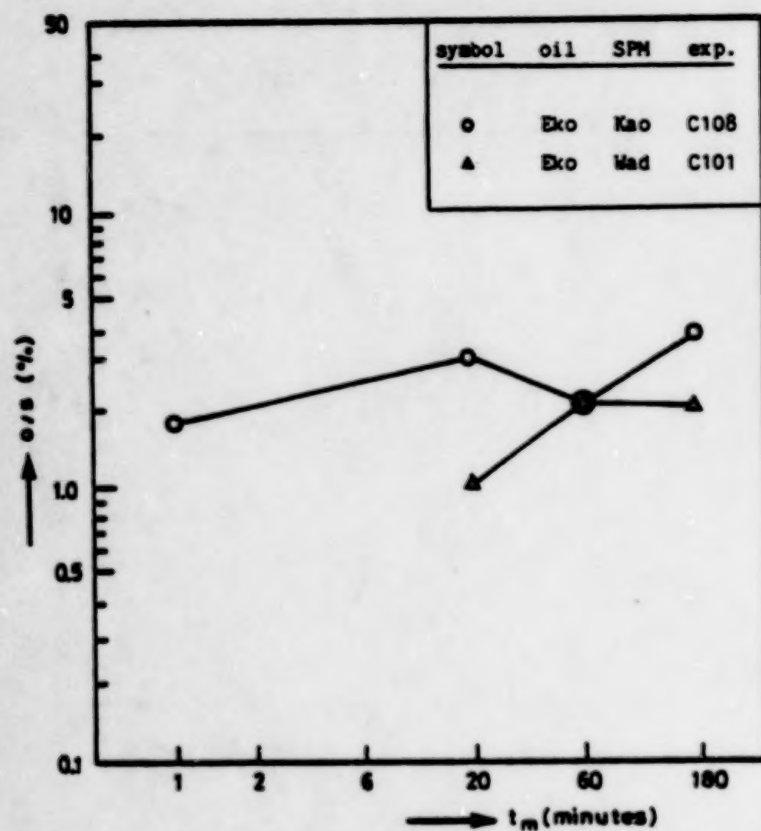


FIGURE IV. 12 Composition of non-buoyant oil-SPM agglomerates over time.
Experiments with different oil types

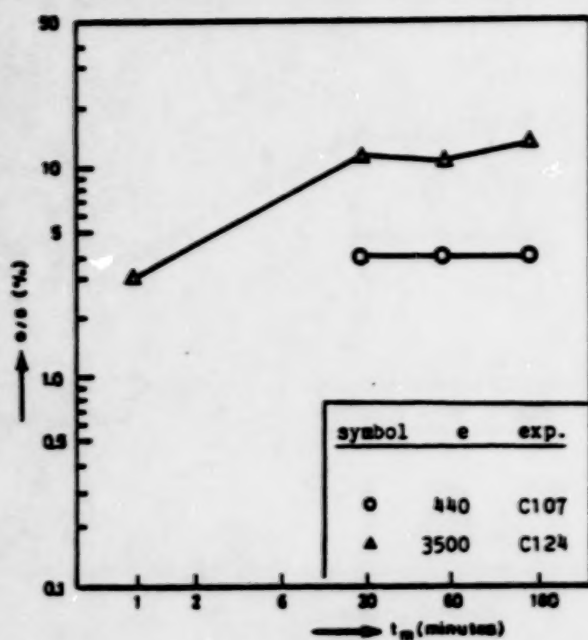


a) PB₃ oil
 $e = 440 \text{ J/s m}^3$

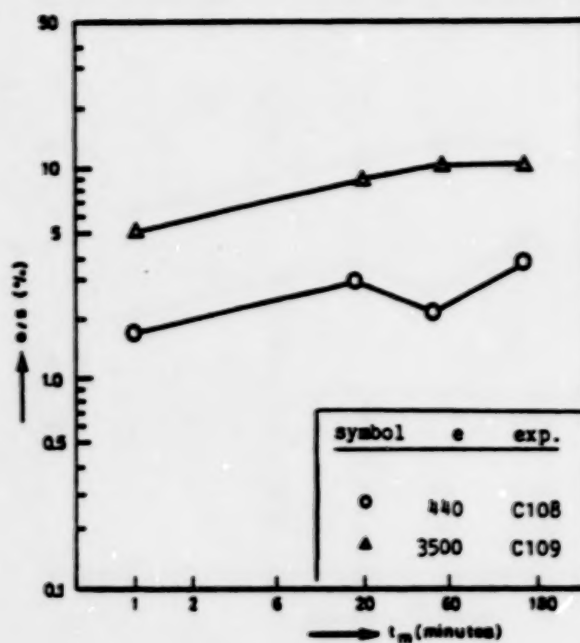


b) Ekofisk oil
 $e = 440 \text{ J/s m}^3$

FIGURE IV. 13 Composition of non-buoyant oil-SPM agglomerates over time.
 Experiments with different SPM types



a) PB_3 + kaolinite



b) Ekofisk + kaolinite

c) Ekofisk + Waddensea silt

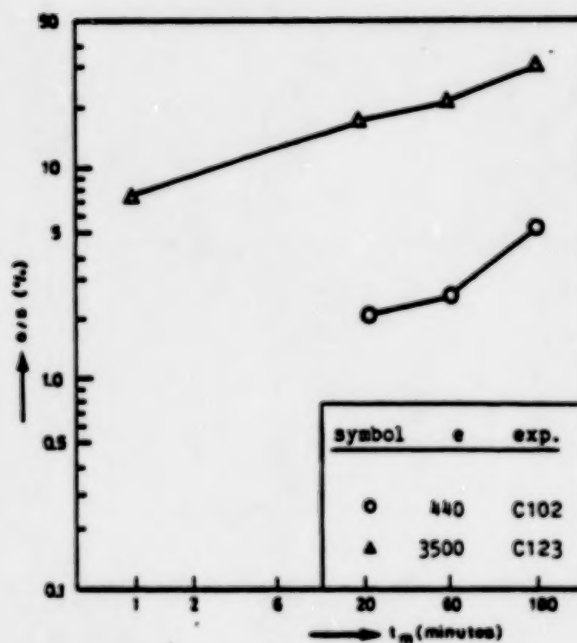


FIGURE IV.14 Composition of non-buoyant oil-SPM agglomerates over time.
Experiments with different turbulent energy levels, e .

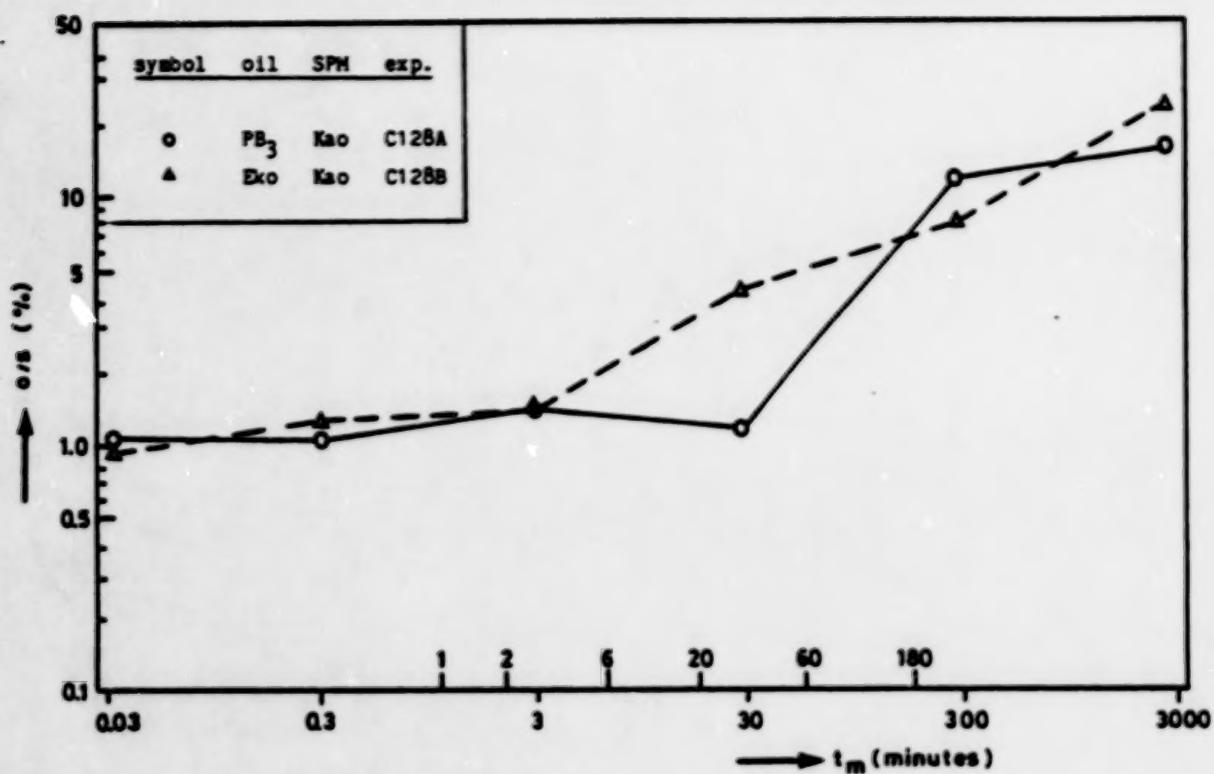
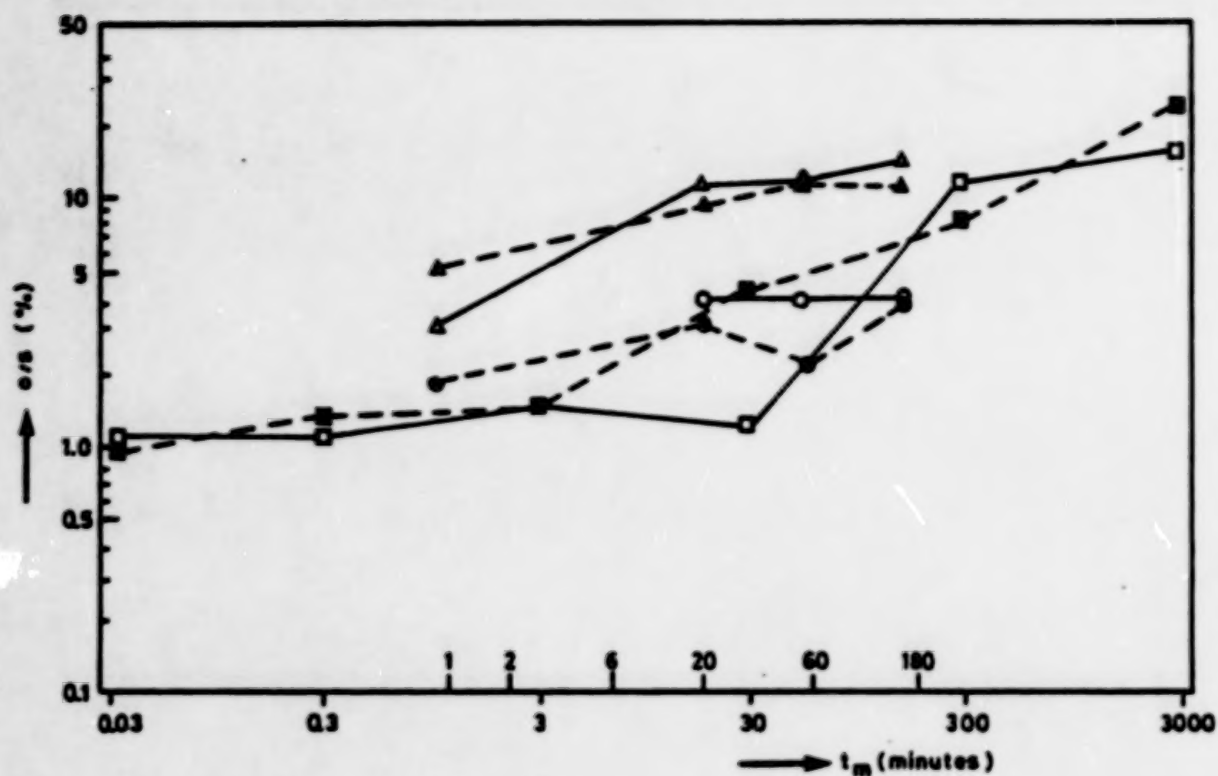


FIGURE IV.15 Composition of non-buoyant oil-SPM agglomerates over time. Stirred-beaker experiments.



symbol	oil	SPM	e	facility	exp.
○	PB ₃	Kao	440	grid column	C107
△	PB ₃	Kao	3500	grid column	C124
□	PB ₃	Kao	**	stirred beaker	C128A
●	Eko	Kao	440	grid column	C108
▲	Eko	Kao	3500	grid column	C109
■	Eko	Kao	**	stirred beaker	C128B

(** stirred beaker with unknown value of e)

FIGURE IV. 16 Composition of non-buoyant oil-SPM agglomerates over time. Experiments in different laboratory facilities and with different turbulent energies.

with kaolinite then with Waddensea silt. It is not assumed that turbulence plays a role in this difference, but it is reasonable to assume that fractionating of the oil is more important in the interaction with Waddensea silt, containing seven percent of organic carbon, than with the "inert" kaolinite without organic carbon. Apparently, equilibrium was obtained within 20 minutes as far as turbulence was concerned, while the fractionating of oil and subsequent changing oil-SPM interaction could take several hours in the applied conditions.

- b) Experiments with equal oil concentrations but different SPM concentrations (kaolinite as well as Waddensea silt) showed equal amounts of oil in the phase III samples independent of the SPM concentration. (Figure IV.11a,b shows the o/s ratios for these experiments). Apparently the number of (small) oil droplets was critical in the experiments with the applied oil and SPM concentration.
- c) Experiments with decreasing oil (FB_0) concentration and decreasing SPM (kaolinite) concentration resulted in almost equal o/s ratios for the highest and medium concentrations. This behaviour is in agreement with conclusion b. However, a considerably lower value of o/s was observed for the lowest oil and SPM concentrations. (Figure IV.10). This could be due to the rapidly decreasing number of collisions between droplets and particles and therefore decreasing interaction rate. If the number of collisions is supposed to limit the o/s ratio, then the o/s ratio must increase with increasing interaction time t_m . Indeed this seemed true in the low concentration experiment, while in other experiments the ratio is constant for kaolinite SPM, although the o/s data are not reliable enough for a firm statement.
- d) Increasing energy dissipation rate ϵ led to increasing o/s ratio, probably due to (1) increasing number of small oil droplets, (2) increasing number of collisions, and/or (3) different flocculation processes. (Figure IV.14).

- e) In the stirred beaker experiments (C128A, C128B), the surface oil was intruded in the water column at $t_m = 0$ by rapid stirring during a few seconds. Subsequently, a considerable part of the oil was kept in suspension by moderate stirring. It was concluded from the constant o/s ratio for $t_m = 2$ seconds to 3 minutes that the small oil droplets were formed within the period of rapid stirring. (Figure IV.15, see also conclusion a.).
- f) All experiments showed declining residual SPM concentration with increasing interaction time. (An additional "blank" experiment without oil resulted in residual SPM concentrations independent of t_m). Apparently, the oil - SPM interaction led to less agglomerates with almost neutral buoyancy. (See also result g.)
- g) Increasing energy dissipation rate led to decreasing residual SPM concentration, except in experiments resulting in very high o/s ratios. (An explanation may be that the high oil - SPM interaction with high e values resulted in bigger flocs and, therefore more sedimentation in stationary samples, except in case of very high oil adsorption that may have led to buoyant flocs, see also result f).
- h) The ranking of oil for oil adsorption on silt depends on the silt. PB₃ and Ekofisk were equally adsorbed by kaolinite, but Ekofisk was considerably better adsorbed by Waddensea silt than PB₃. (Figure IV.12).
- j) Kaolinite adsorbed more oil than Waddensea silt in experiments with $e = 440 \text{ J/s m}^3$, but Waddensea silt adsorbed more oil than kaolinite in case of $e = 3500 \text{ J/s m}^3$. (Figures IV.12 and IV.14).
- k) PB₃ was more adsorbed by SPM than PB₀, and led to less residual SPM in the samples than PB₀. (Figure IV.12a).
- l) The o/s ratio with Waddensea silt was considerably more variable than with kaolinite. The o/s ratios ranged from 0.15 to 34 % with Waddensea silt, and from 1.9 to 12.7 % with kaolinite, in similar series of

experiments. (Figures IV.12 and IV.14).

- m) The rapidly increasing o/s ratio in experiment C128 after $t_m = 30$ minutes was apparently due to emulsification of the oil. This was clearly observed in the experiments C128A (see also Section IV.6.1). (Note: No surface oil was present and therefore no emulsification took place in the grid column experiments).
- n) The GC hydrocarbon composition data in Table IV.2 indicated that the low-alkanes concentration was highest for surface oil (phase I), moderate for sedimentated matter (phase III), and lowest for SPM remaining in suspension (phase II). The most simple explanation for these composition differences is that loss of low-alkanes by evaporation or dissolution was relatively high for the most dispersed oil (i.e. lowest concentration of oil in a sample), see Table IV.2, column 25.

IV.6 Results from Visual Microscopy

Visual microscopy of the samples from the different oil - SPM interaction experiments was performed to obtain qualitative and quantitative information on the following questions:

- a) is oil adsorbed by SPM in the form of a thin film on the particles, or as discrete oil droplets?
- b) what is the size of the adsorbed oil droplets in different conditions?
- c) does oil adsorption influence the flocculation behaviour of SPM?
- d) do relatively large oil droplets take-up small SPM particles, and what are the typical particle sizes in this process?

IV.6.1 Description of the micrographs

The results of visual microscopy are illustrated, to the extent possible, by a set of micrographs in the Figures IV.17 to IV.44. Table IV.3 surveys the micrographs, the symbol I or III indicates whether surfaced buoyant material, phase I, or sedimented sample material, phase III, was photographed. The number in between brackets refers to the figure number in

Table IV.3 Micrographs and microscope observations of oil - SPM samples

Run No	oil type, C_0	Legend: Phase I = buoyant portion of sample Phase III = sedimented portion of sample <u>c</u> = phase III sedimented in 5 mm sample cell <u>b</u> = phase III sedimented in 250 mm bottle (..), number in brackets refers to figure number IV (..)				
		Interaction time t_m (min)				Remarks on observations
		1	20	60	180	
turbulence SPM type, C_s level e ($J/s\ m^3$)	C125 FB_0 , 100 ppm $e = 3500$ Kao, 60 ppm	III(20) <u>b</u>	I(17) III(21) <u>c</u>	I(18)	I(19) III(22) <u>c</u>	Similar d_0 distribution in all III samples ^a : $d_{max} = 60\ \mu m$, $d_{min} = 2\ \mu m$. Similar coating of oil droplets in all I samples.
	C126 FB_0 , 35 ppm $e = 3500$ Kao, 20 ppm		I(23) big droplets coated with SPM, small droplets uncoated		I(24) III(25) <u>c</u>	
	C127 FB_0 , 10 ppm $e = 3500$ Kao, 6 ppm		I(26) Only 10 percent of droplets is coated.	III(28) <u>c</u>	I(27) similar as 20 min. sample III(29) <u>c</u>	
C124 FB_3 , 100 ppm $e = 3500$ Kao, 60 ppm C107 FB_3 , 100 ppm $e = 440$ Kao, 60 ppm				III(31) <u>b</u>	I(30) III(32) <u>b</u>	In all III samples ^a : $d_{max} = 60\ \mu m$, $d_{50} = 20\ \mu m$. In all III samples ^a : $d_{max} = 60\ \mu m$, $d_{50} = 20\ \mu m$.
	C105 FB_3 , 100 ppm $e = 440$ Mad, 7.3 ppm C88 FB_3 , 100 ppm $e = 440$ Mad, 15 ppm C103 FB_3 , 100 ppm $e = 440$ Mad, 30 ppm					In all III samples ^a : $d_{max} = 40\ \mu m$, $d_{50} = 15\ \mu m$. In all III samples ^a : $d_{max} = 50\ \mu m$, $d_{50} = 15\ \mu m$. Increase of oil in III samples with increasing t_m .
C106	FB_3 , 100 ppm Mad, 75 ppm		III(33) <u>b</u>	III(34) <u>b</u>	III(35) <u>b</u>	Similar III samples ^a with: $d_{max} = 50\ \mu m$, $d_{50} = 15\ \mu m$.

Table IV.3 (continued)

Run No	oil type, C_o turbulence SPN type, C_s e ($J/s\ m^3$)	Interaction time t_m (min)				Remarks on observations
		1	20	60	180	
C108	Eko, 100 ppm $e = 440$					In all III samples ^a : $d_{max} = 70\ \mu m$, $d_{50} = 30\ \mu m$.
C109	Eko, 100 ppm $e = 3500$		III(36) <u>c</u>			In all III samples ^a : $d_{max} = 50\ \mu m$, $d_{50} = 20\ \mu m$.
C101	Eko, 100 ppm $e = 440$					
C102	Eko, 100 ppm $e = 440$		III(37) <u>b</u>		III(38) <u>b</u>	In all III samples ^a : $d_{max} = 60\ \mu m$, $d_{50} = 20\ \mu m$.
C123	Eko, 100 ppm $e = 3500$		III(39,40) <u>b</u>	III(41,42) <u>b</u>	III(43) <u>b</u>	In all III samples ^a : $d_{max} = 70\ \mu m$, $d_{50} = 20\ \mu m$, $d_{min} = 2\ \mu m$. Increase of oil in III samples with increasing t_m .
C128A	FD ₃ , 100 ppm stirred beaker			$t_m = 50\ h$ I(44)		Emulsification in all $t_m \geq 5h$ samples, not in $t_m \leq 1/2 h$ samples. Oil droplets and emulsified filaments in phase III, at $t_m = 50\ h$, with: $d_{max} = 25\ \mu m$, $d_{50} = 8\ \mu m$, $d_{min} = 2\ \mu m$.
C128B	Eko, 100 ppm stirred beaker					No visible emulsification with Eko, neither in phase I nor in phase III. In phase III sample at $t_m = 50\ h$: $d_{max} = 20\ \mu m$, $d_{50} = 5\ \mu m$, $d_{min} = 2\ \mu m$.

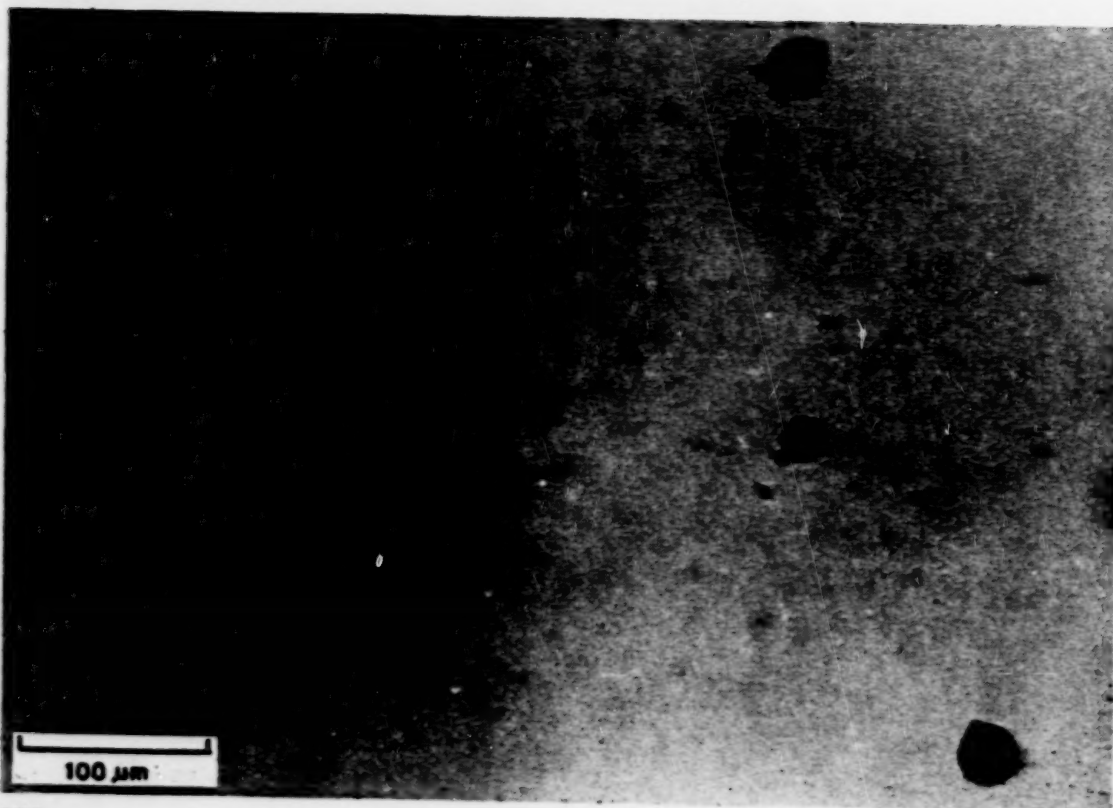
^a Almost all phase III samples with $t_m = 1\ min$. seem to have a higher value of d_{50} and especially, a considerable lower number of very small droplets absorbed by the sediment. Generally there is no visible difference between the samples (III) at $t_m = 20, 60$ and 180 minutes.

this Section IV.

- a) The experiments C125, C126 and C127 (see Table IV.3) are similar with respect to the type of oil, type of SPM and turbulence level, but the oil and SPM concentrations decline by a factor 3 for C126, and a factor 10 for C127, relative to experiment C125.

The Figures IV.17, IV.18 and IV.19 show micrographs of SPM-coated buoyant oil droplets from C125 samples, withdrawn at $t_m = 20, 60$ and 180 minutes respectively. All droplets were heavily coated, and looked similar for the three samples. The Figures IV.23 and IV.24 show SPM-coated droplets in experiment C126, at $t_m = 20$ and 180 minutes. The reduced oil and SPM concentration resulted in uncoated small droplets, but still heavily coated big droplets. The $t_m = 20$ and $t_m = 180$ minutes samples of experiment C127, with even less oil and SPM concentration, show only 10 percent of the oil droplets being coated. (See Figures IV.26 and IV.27).

Micrographs of oiled sediment in the experiments C125, C126 and C127 are given in Figures IV.20, IV.21, IV.22, IV.25 IV.28 and IV.29. Almost all figures consist of two subfigures. The micrograph in subfigures a was taken by application of the UV light source to record most clearly the fluorescent oil droplets, while for subfigures b the visible light source was used to record the SPM particles as well. (The subfigures b give some information on the floc sizes. However it should be noted that the floc sizes were not only dependent on the experimental conditions in the grid column, but certainly also on the sedimentation conditions in the sample bottle or sample cell). The C125 samples removed at $t_m = 1, 20$ and 180 minutes (see Figure IV.20, IV.21 and IV.22 respectively) showed similar size distributions for the oil droplets captured in the SPM agglomerates. The maximum droplet size was $d_{max} = 60 \mu m$ (visual observation, not shown on the micrographs), the minimum size observed was $d_{min} = 2 \mu m$ (= limit of routine observation). The oiled-sediment samples of the experiments C126 and C127 (see Figures IV.25, IV.28 and IV.29) contained oil droplets with smaller maximum sizes down to $d_{max} = 20 \mu m$ for the experiment C127 with the lowest oil and SPM concentration. The occurrence of smaller



250x

FIGURE IV. 17 Oil-SPM experiment C125 $t_m = 20$ min.
Micrograph of SPM-coated buoyant oil droplets

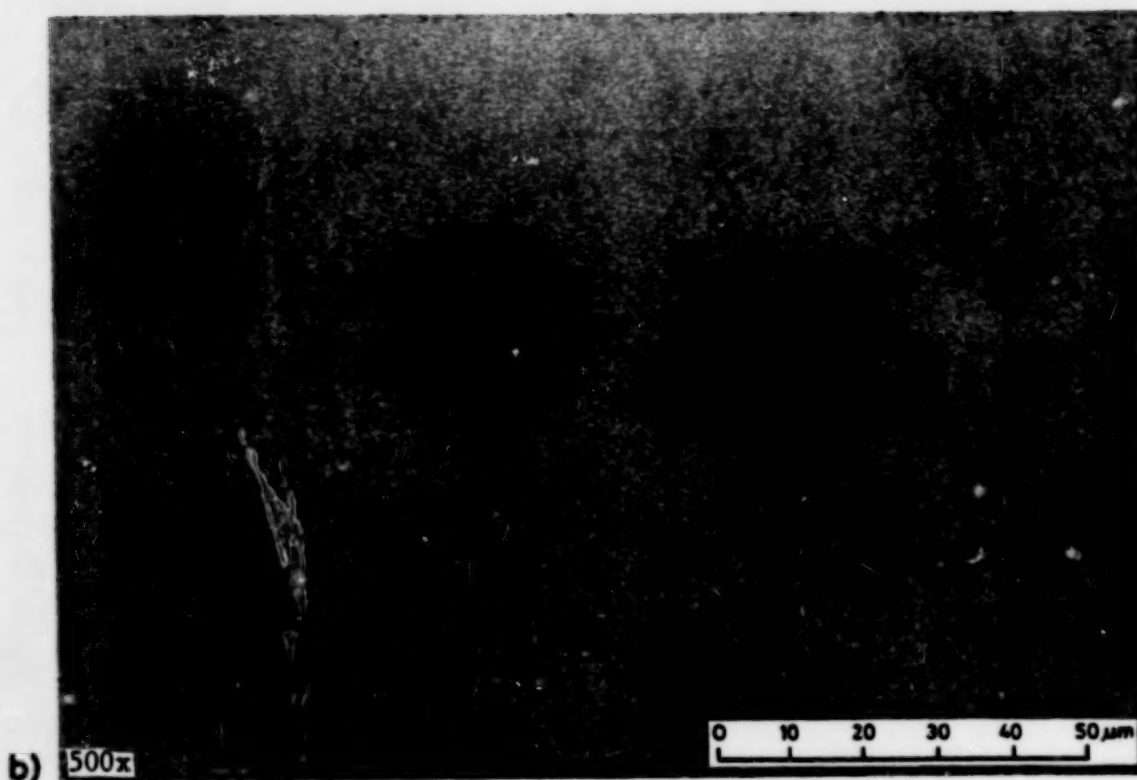
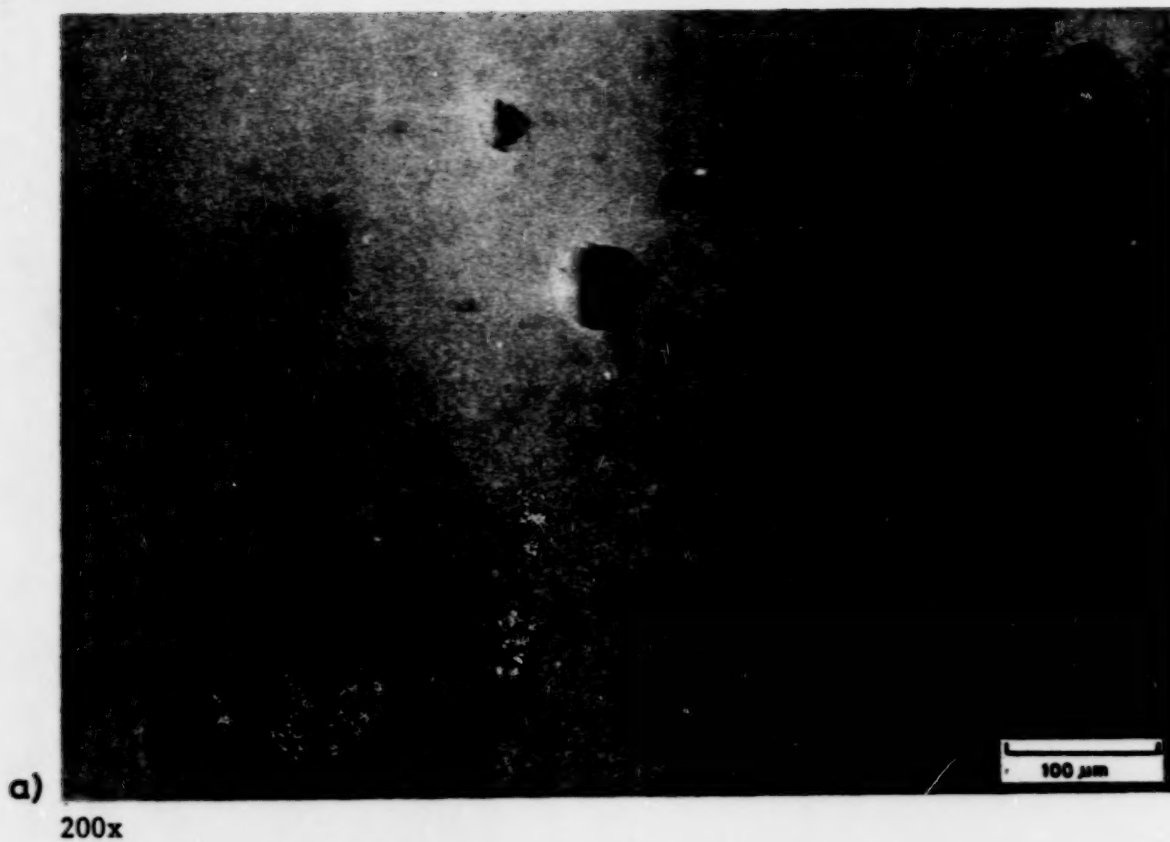
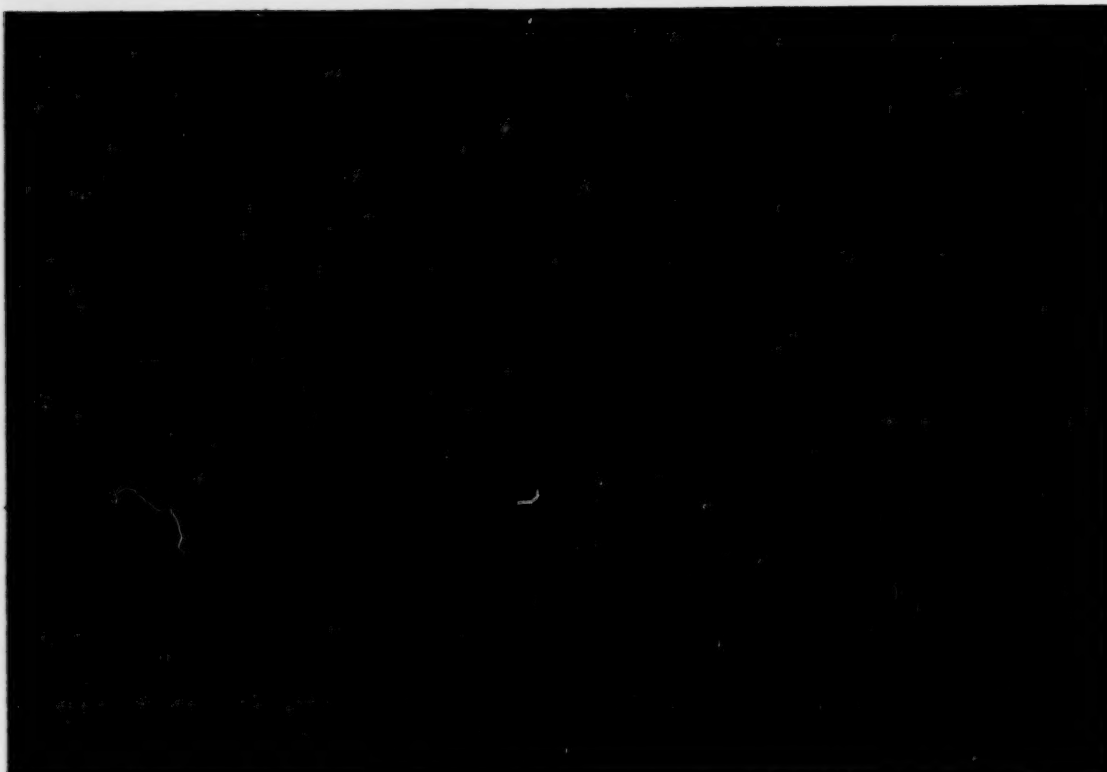


FIGURE IV.18 Oil-SPM experiment C125 $t_m = 60$ min.
Micrographs of SPM-coated buoyant oil droplets



a)

250x, visible light

100 μ m

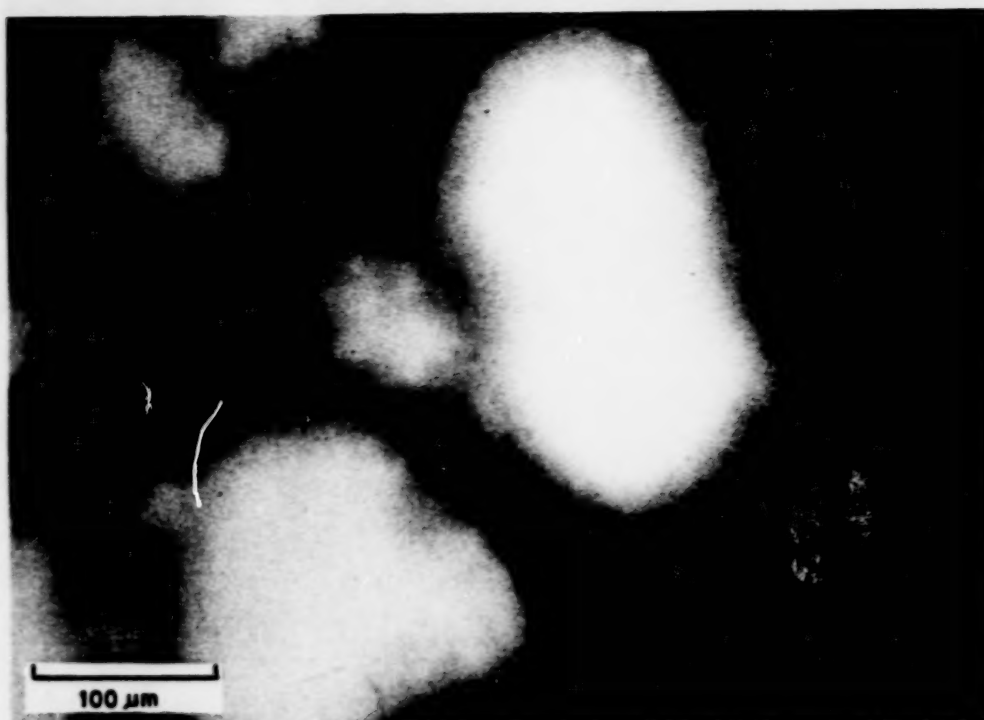


b)

250x, UV light

FIGURE IV.19 Oil-SPM experiment C125 $t_m = 180$ min.

Micrograph of SPM-coated buoyant oil droplets



250x, UV light

FIGURE IV.20 Oil-SPM experiment C125 $t_m = 1$ min.

Micrograph of oiled sediment

a) 250x, UV light



100 μ m

b) 250x, UV + visible light

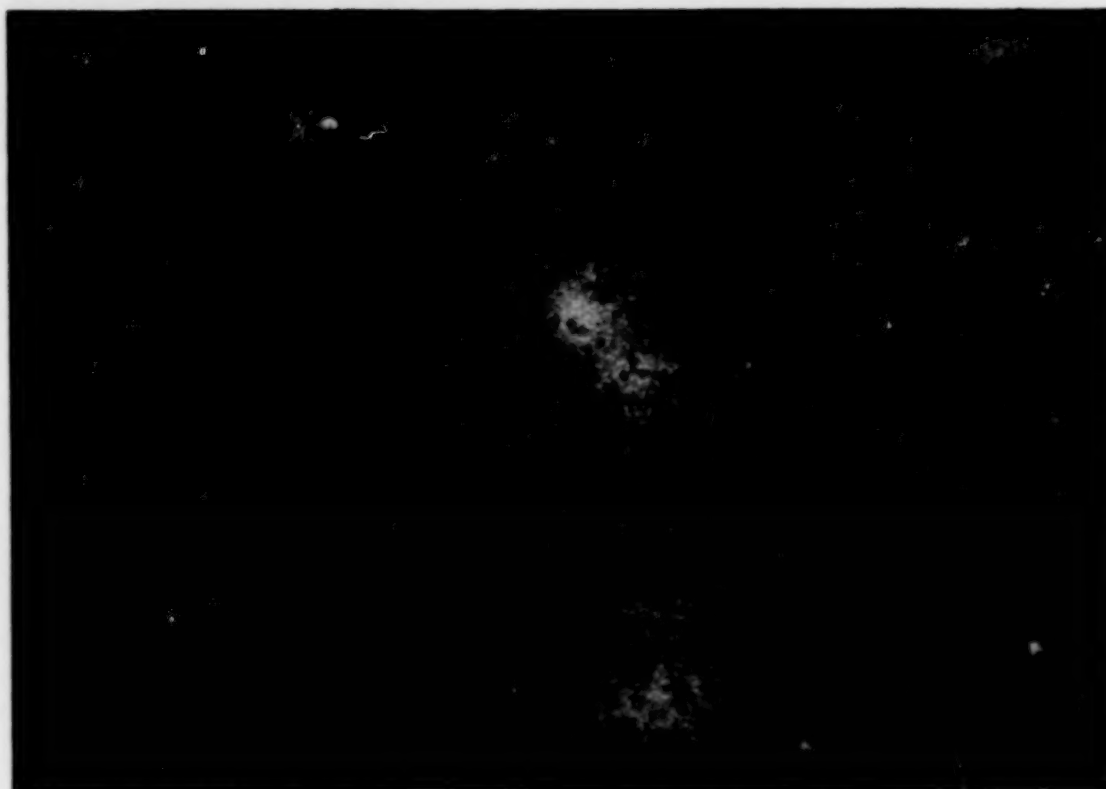
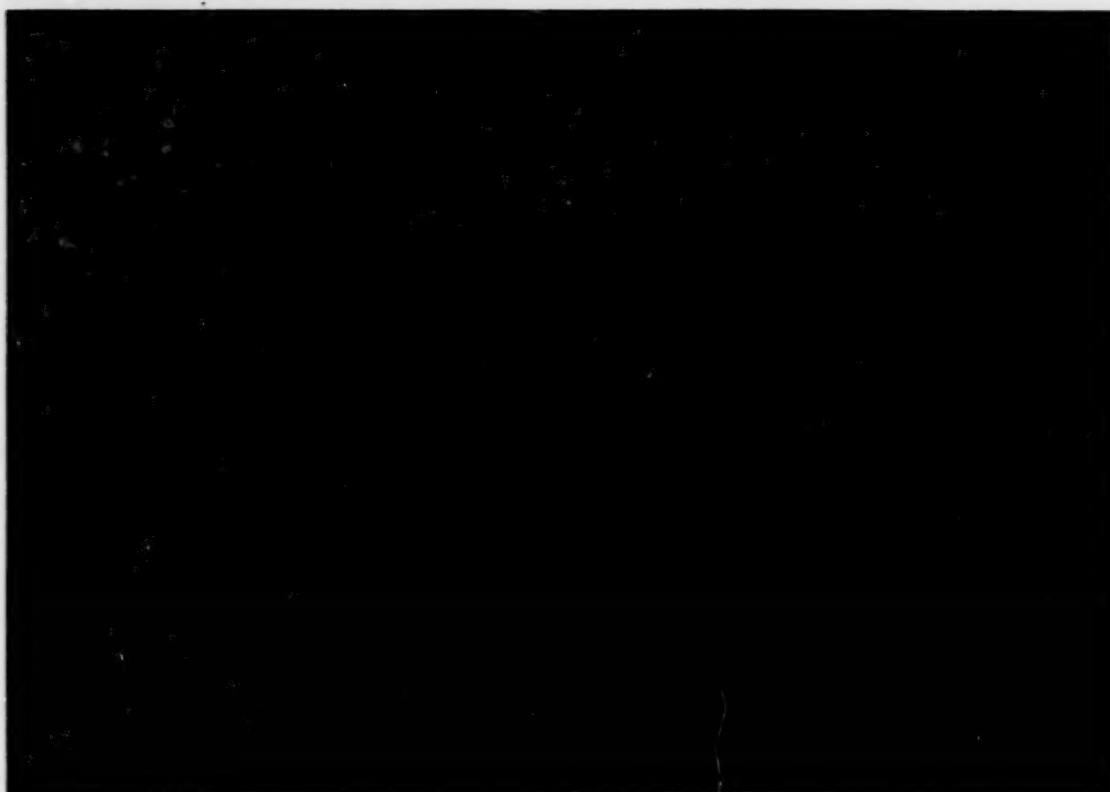


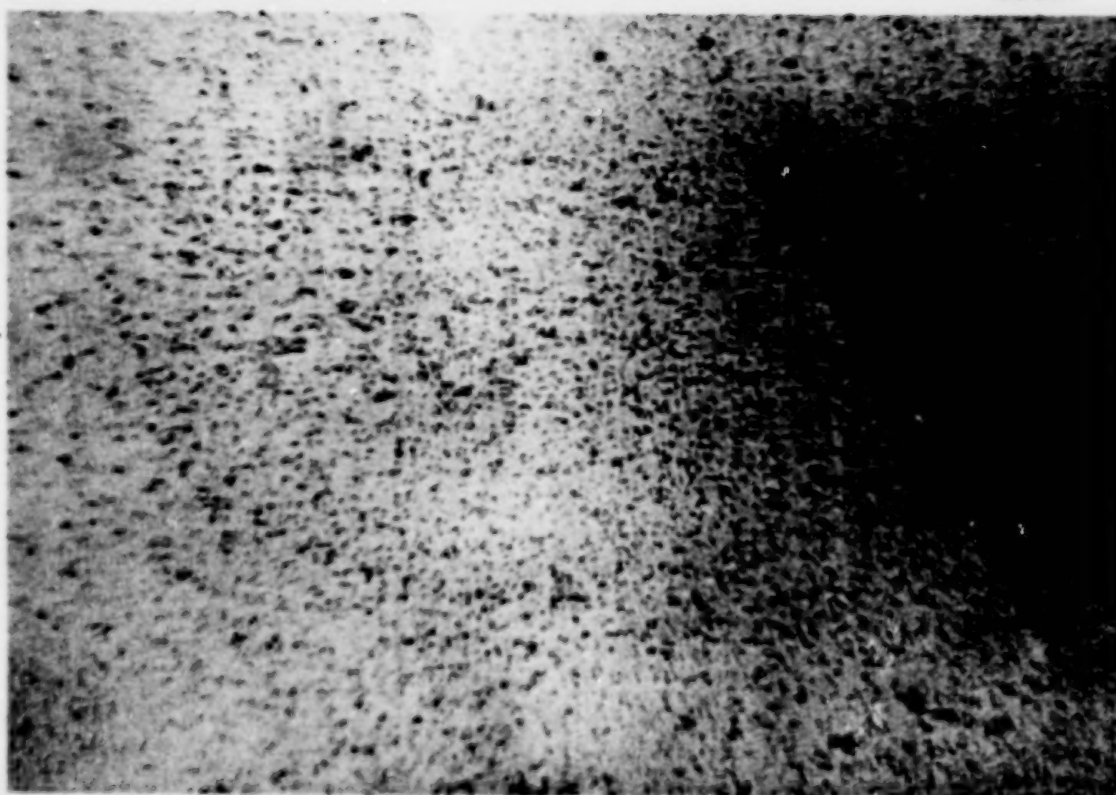
FIGURE IV. 21 Oil-SPM experiment C125 $t_m = 20$ min.

Micrograph of oiled sediment



a)
100x, UV light

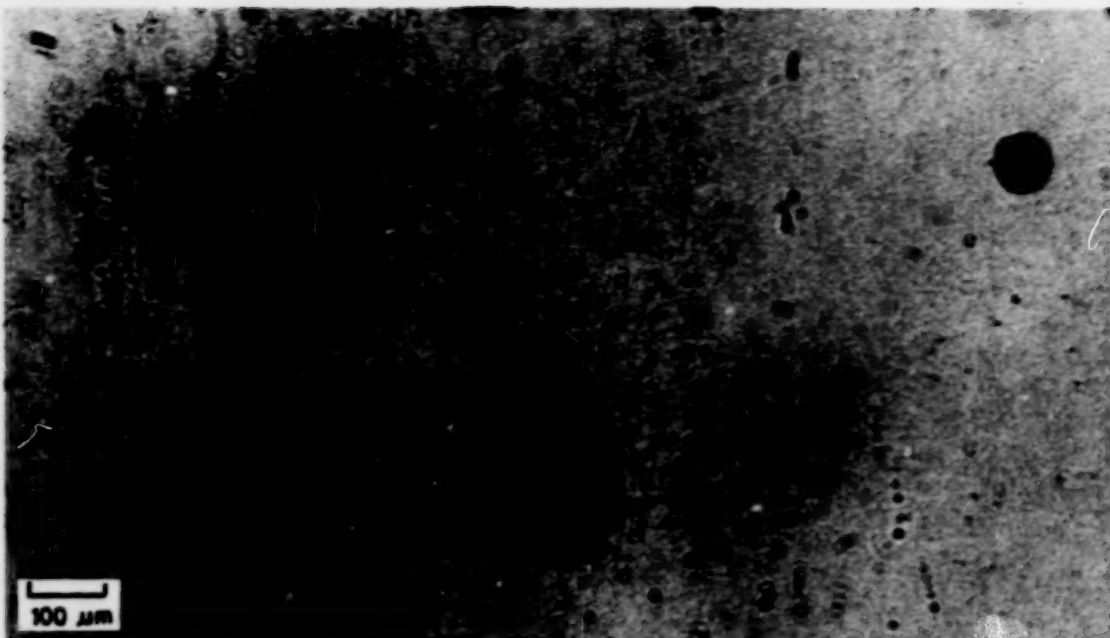
100 μ m



b)
100x, visible light

FIGURE IV. 22 Oil-SPM experiment C125 $t_m = 180$ min.

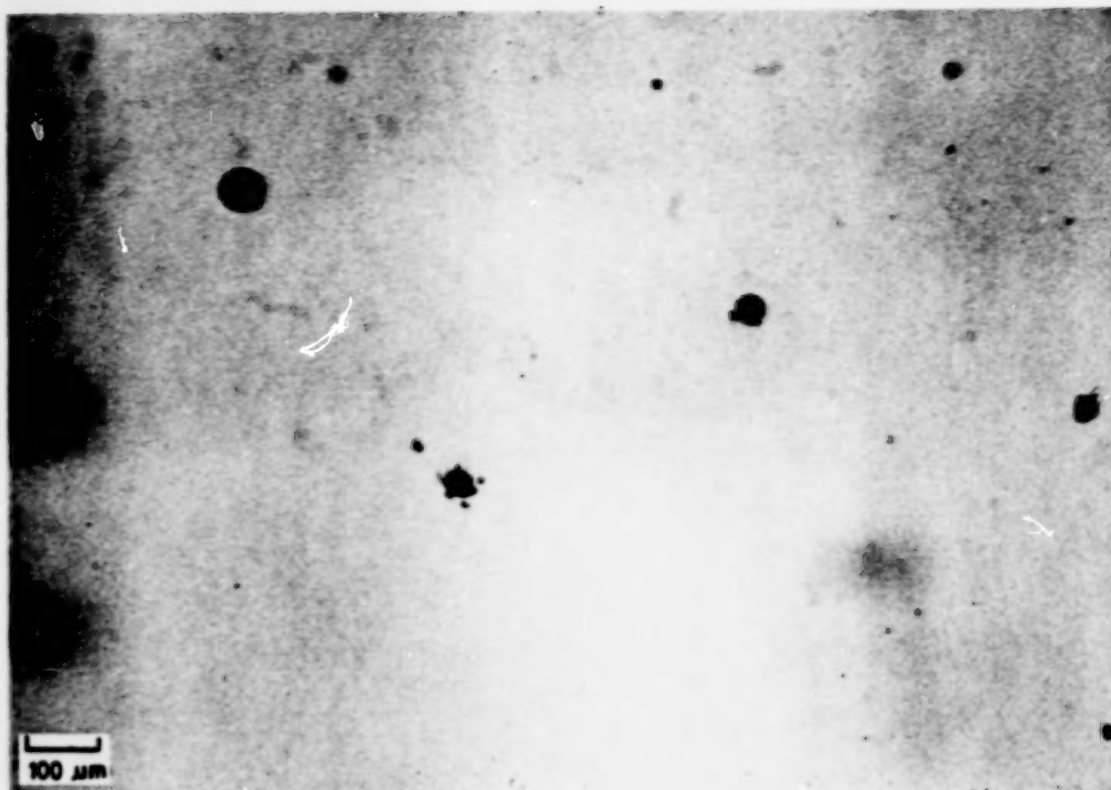
Micrograph of oiled sediment



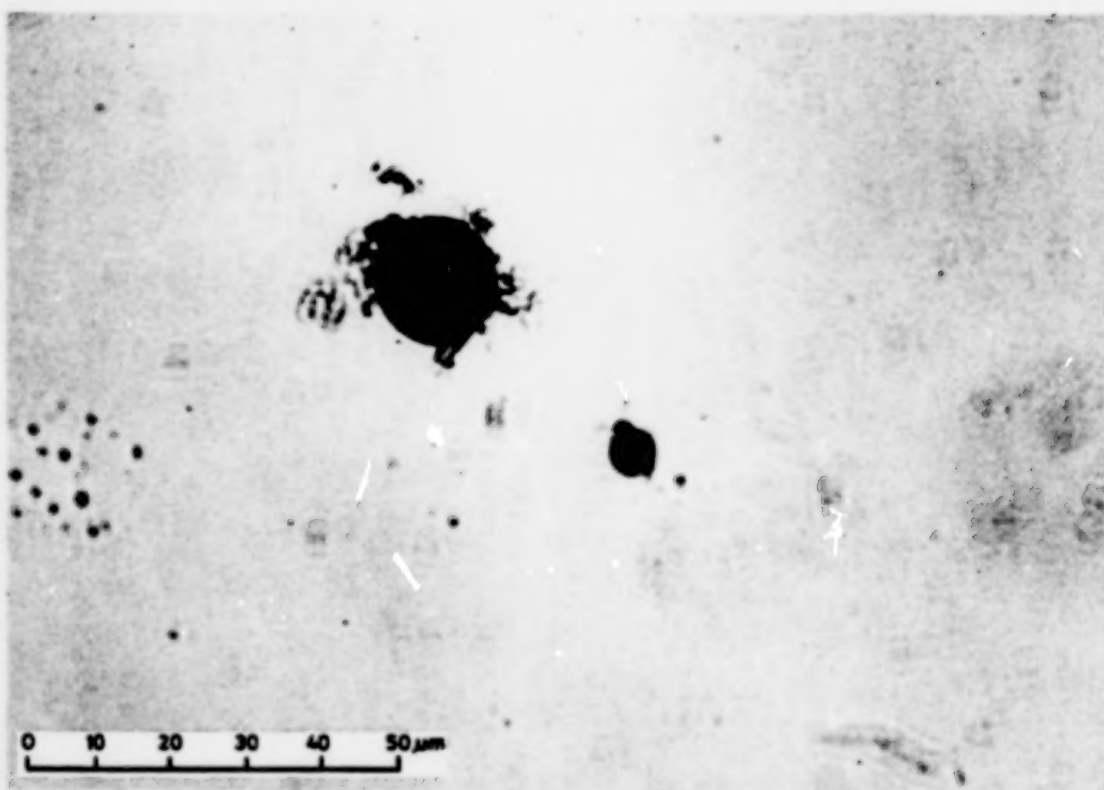
100x, visible light

FIGURE IV. 23 Oil-SPM experiment C126 $t_m = 20$ min.

Micrograph of SPM-coated buoyant oil droplets



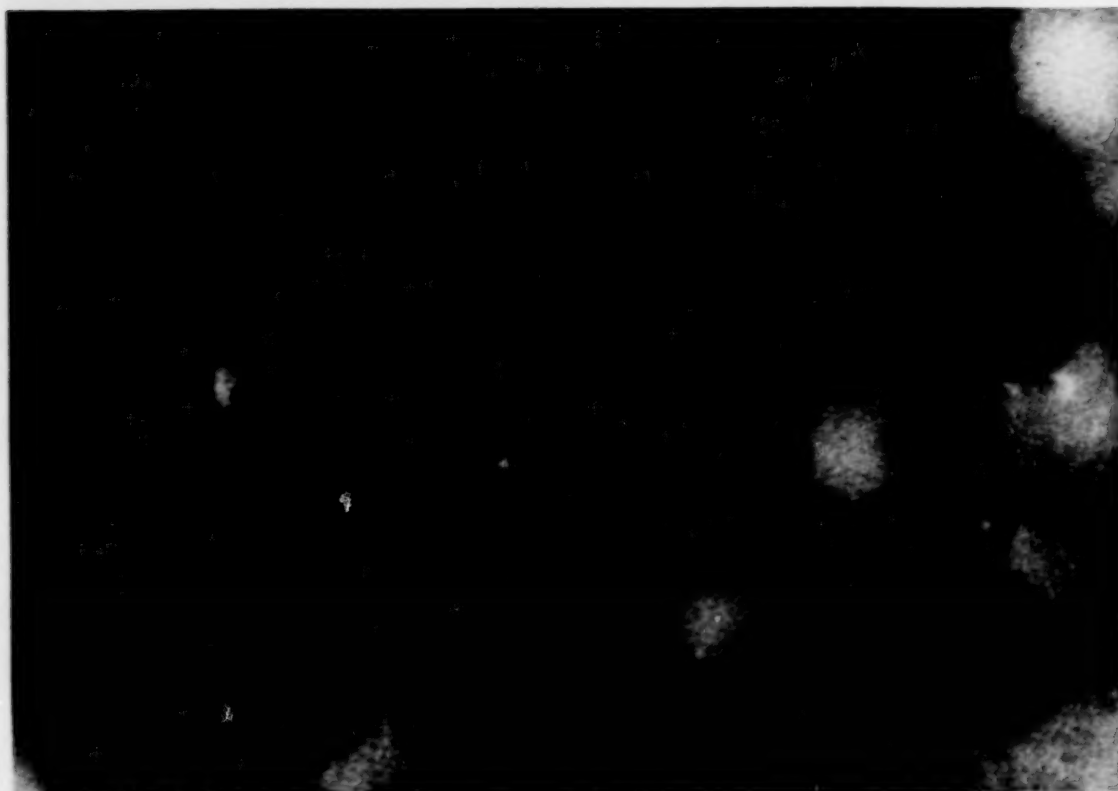
a) 100x, visible light



b) 500x, visible light

FIGURE IV. 24, Oil-SPM experiment C126 $t_m = 180$ min.

Micrographs of SPM-coated buoyant oil droplets



a) 200x, UV light

100 μm



b) 200x, visible light

FIGURE IV. 25 Oil-SPM experiment C126 $t_m = 180$ min.

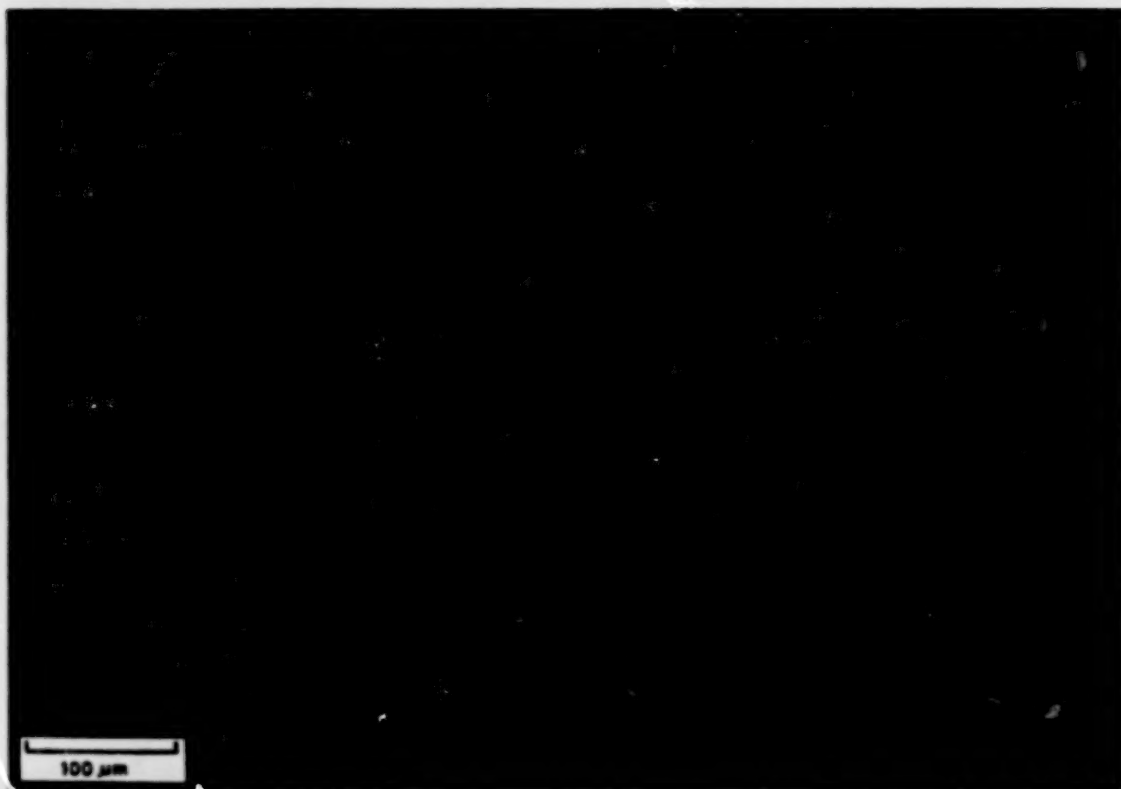
Micrograph of oiled sediment



200x, UV + visible light

FIGURE IV.26 Oil-SPM experiment C127 $t_m = 20$ min. .

Micrograph of buoyant oil droplets

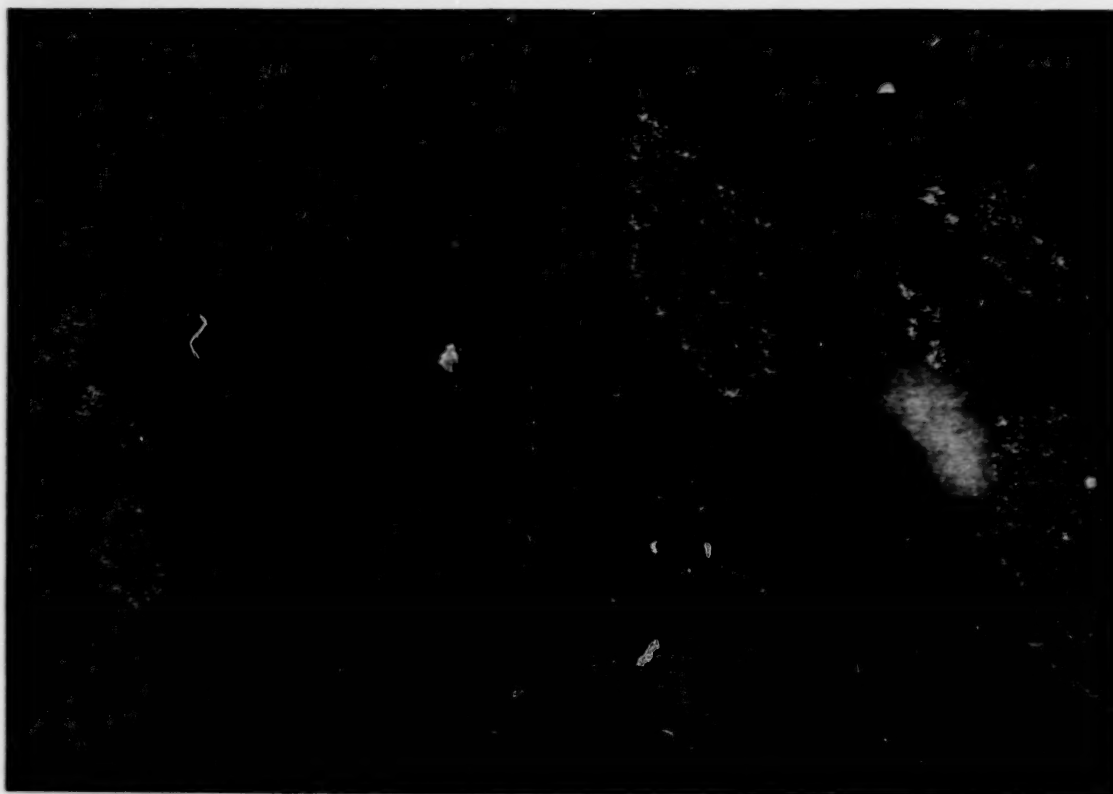


a) 200x, UV + visible light



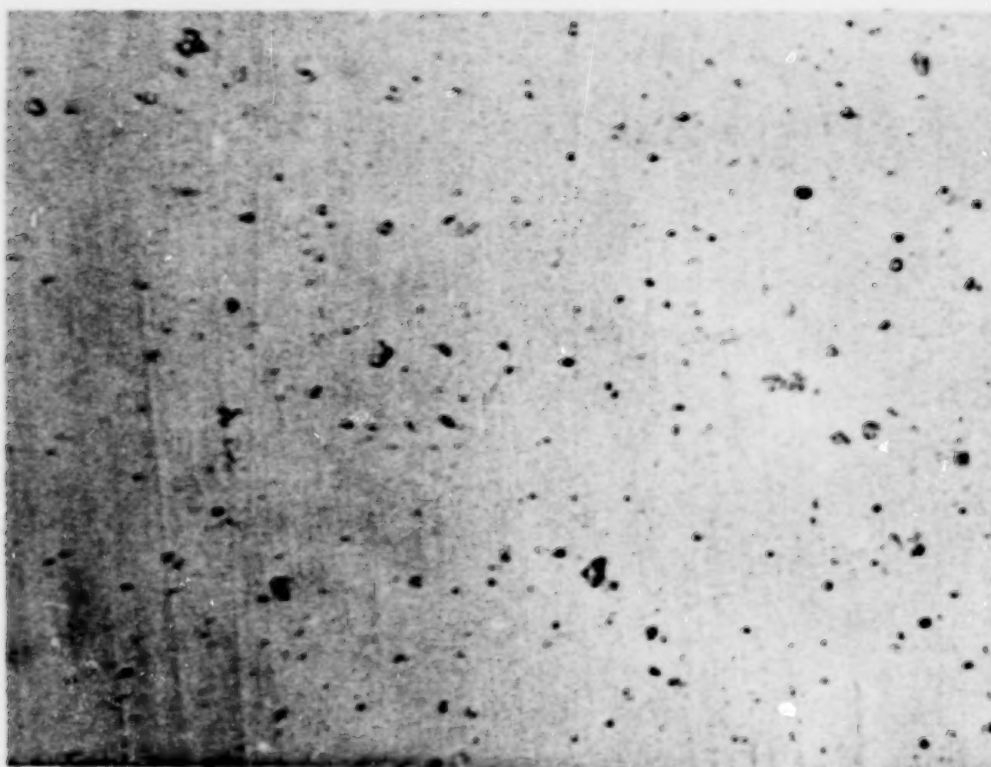
b) 2000x, UV + visible light

FIGURE IV. 27 Oi-SPM experiments C127 $t_m = 180$ min.
Micrographs of buoyant oil droplets



a)
200x, UV light

100 μ m



b)
200x, UV + visible light

FIGURE IV. 28 Oil-SPM experiment C127 $t_m = 60$ min.

Micrograph of oiled sediment

a)

100x, UV light

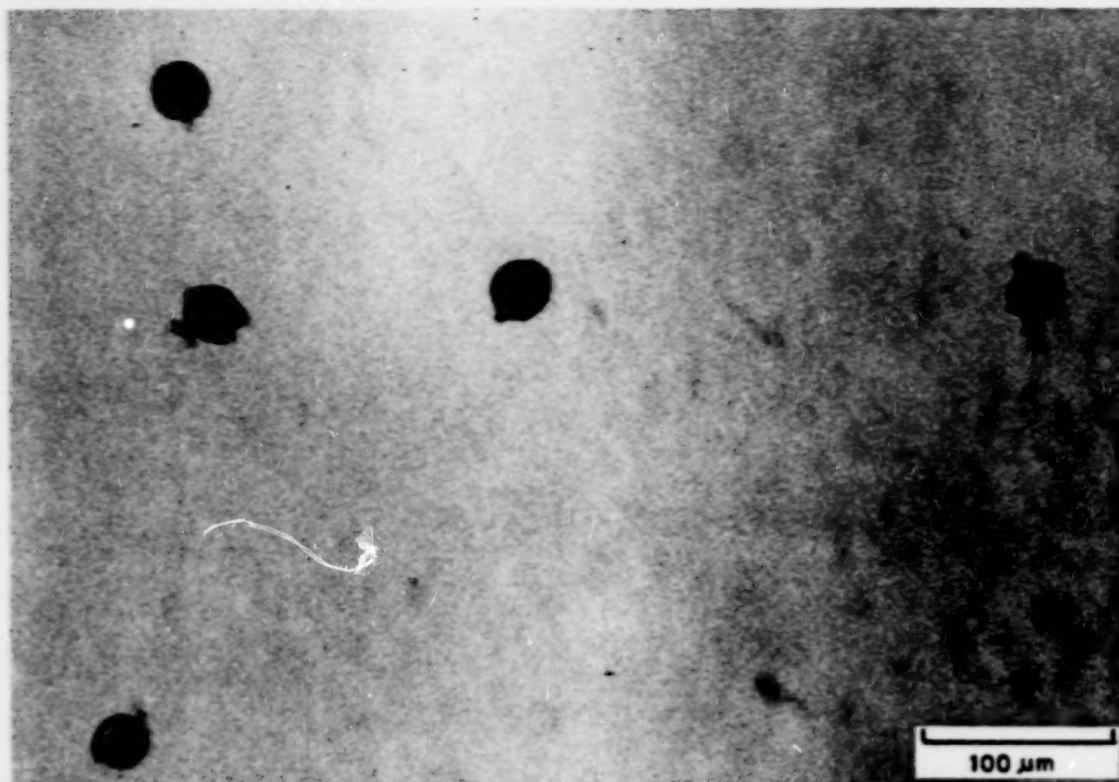
100 μ m

b)

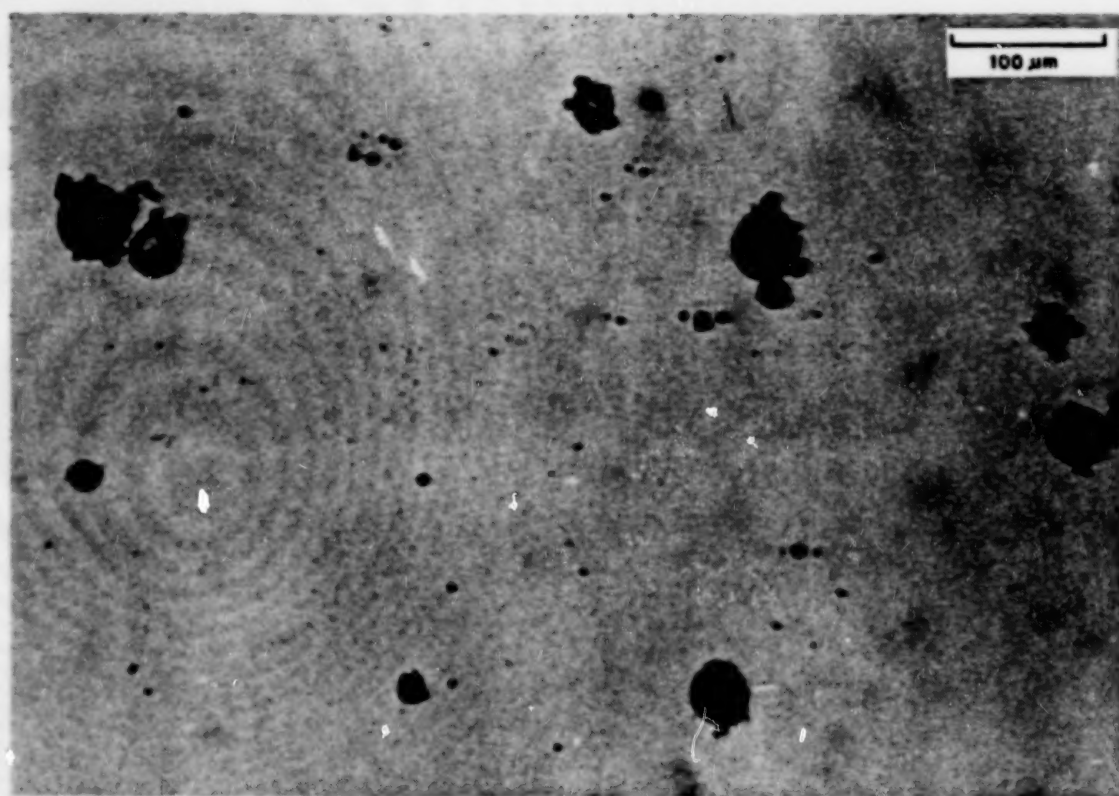
100x, UV + visible light

FIGURE IV. 29 Oil-SPM experiment C127 $t_m = 180$ min.

Micrograph of oiled sediment



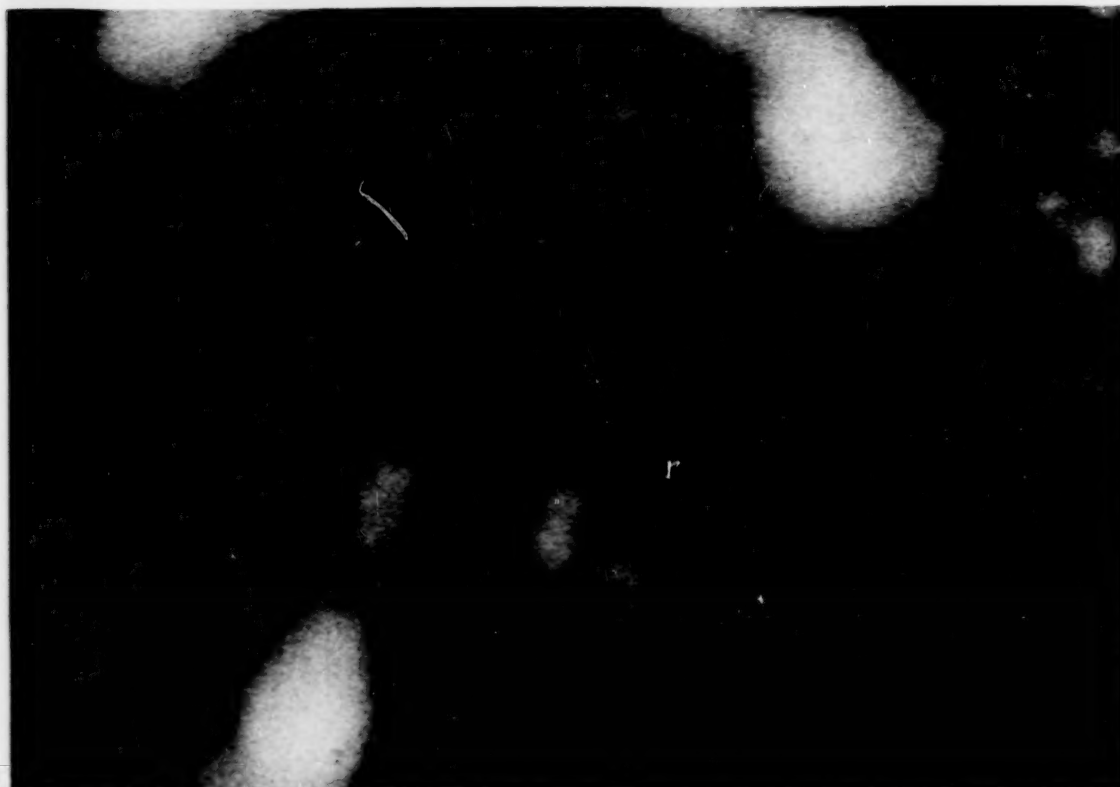
a)
250x, visible light



b)
200x, visible light

FIGURE IV. 30 Oil-SPM experiment C124 $t_m = 180$ min.

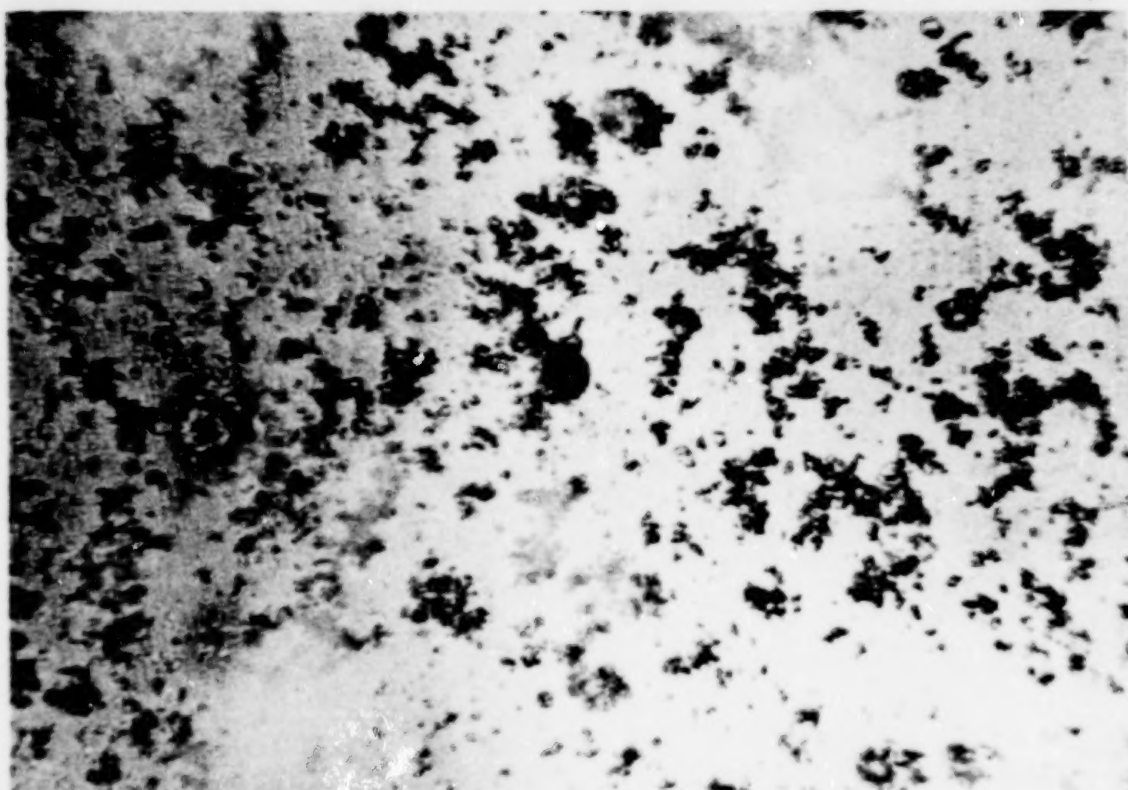
Micrographs of SPM-coated buoyant oil droplets



a)

100x, UV light

100 μ m

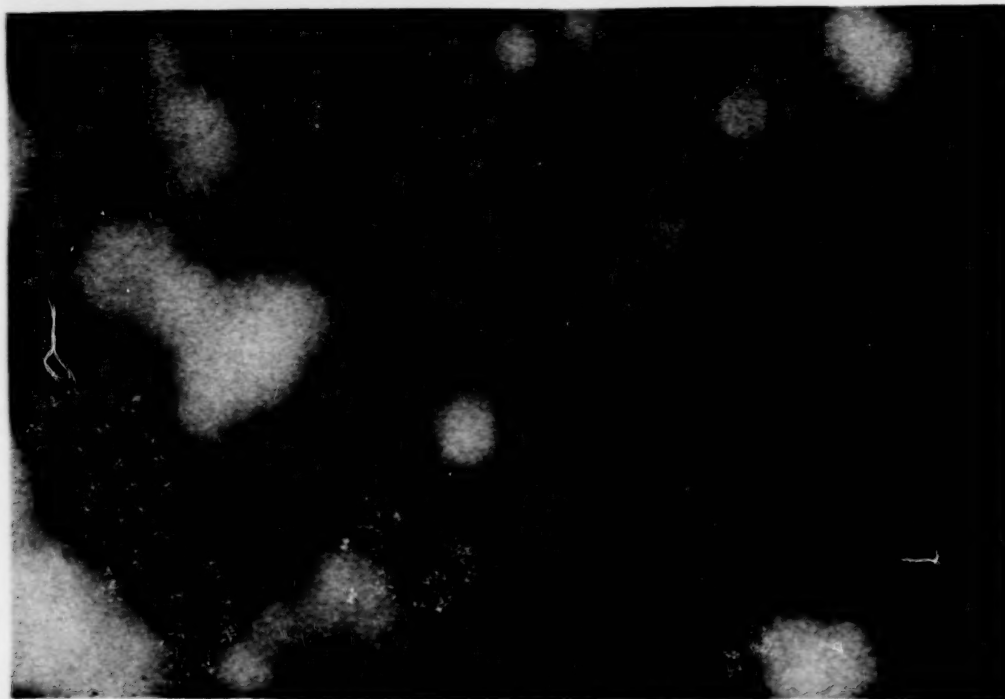


b)

100x, UV + visible light

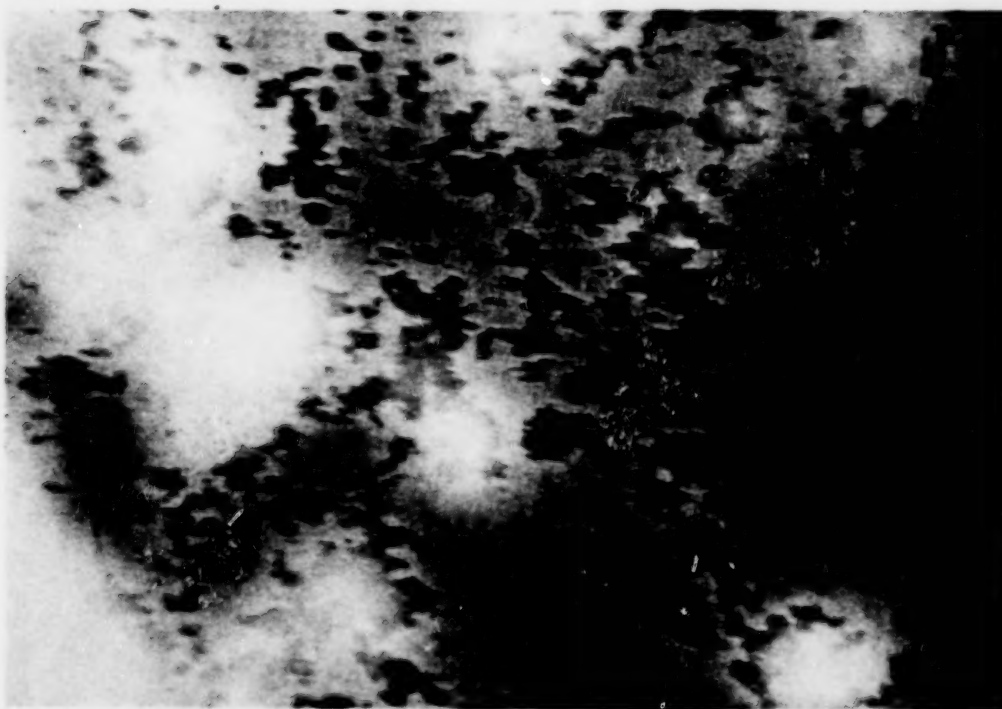
FIGURE IV. 31 Oil-SPM experiment C124 $t_m = 60$ min.

Micrograph of oiled sediment



a)
100x, UV light

100 μ m



b)
100x, UV + visible light

FIGURE IV. 32 Oil-SPM experiment C124 $t_m = 180$ min.
Micrograph of oiled sediment



a)
200x, UV light

100 μm



b)
200x, UV + visible light

FIGURE IV. 33 Oil-SPM experiment C106 $t_m = 20$ min.

Micrograph of oiled sediment



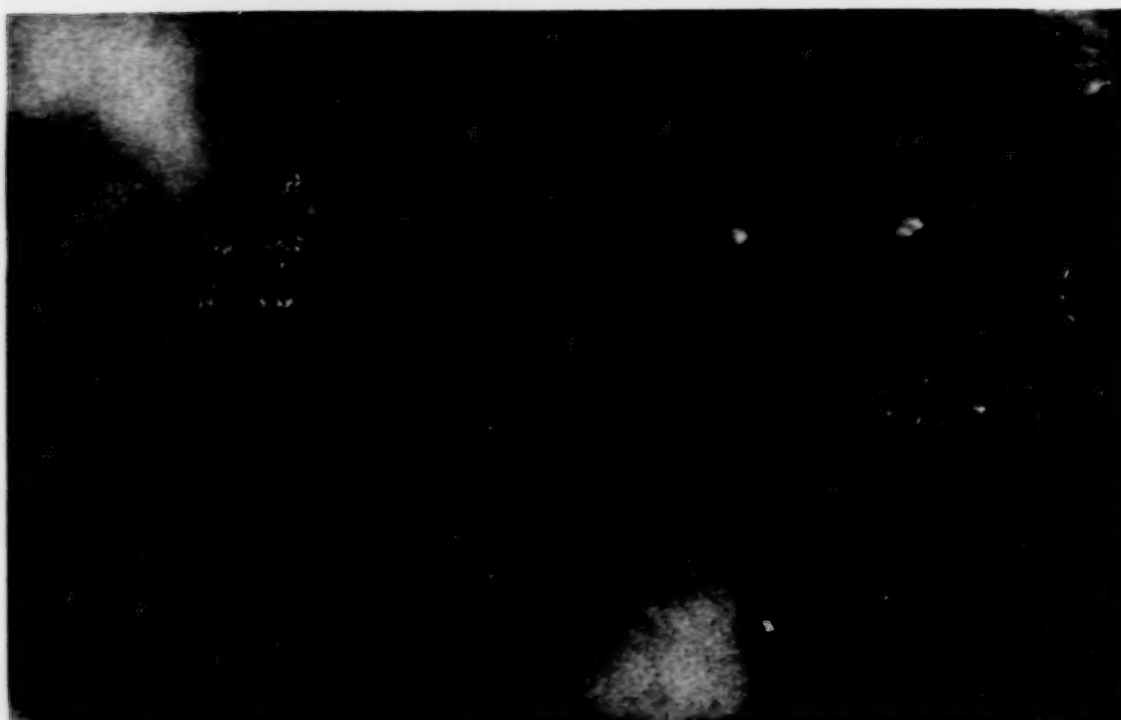
a)
200x, UV light

100 μm



b)
200x, UV + visible light

FIGURE IV. 34 Oil-SPM experiment C106 $t_m = 60$ min.
Micrograph of oiled sediment



a) 200x, UV light

100 μ m



b) 200x, UV + visible light

FIGURE IV. 35 Oil-SPM experiment C106 $t_m = 180$ min.

Micrograph of oiled sediment

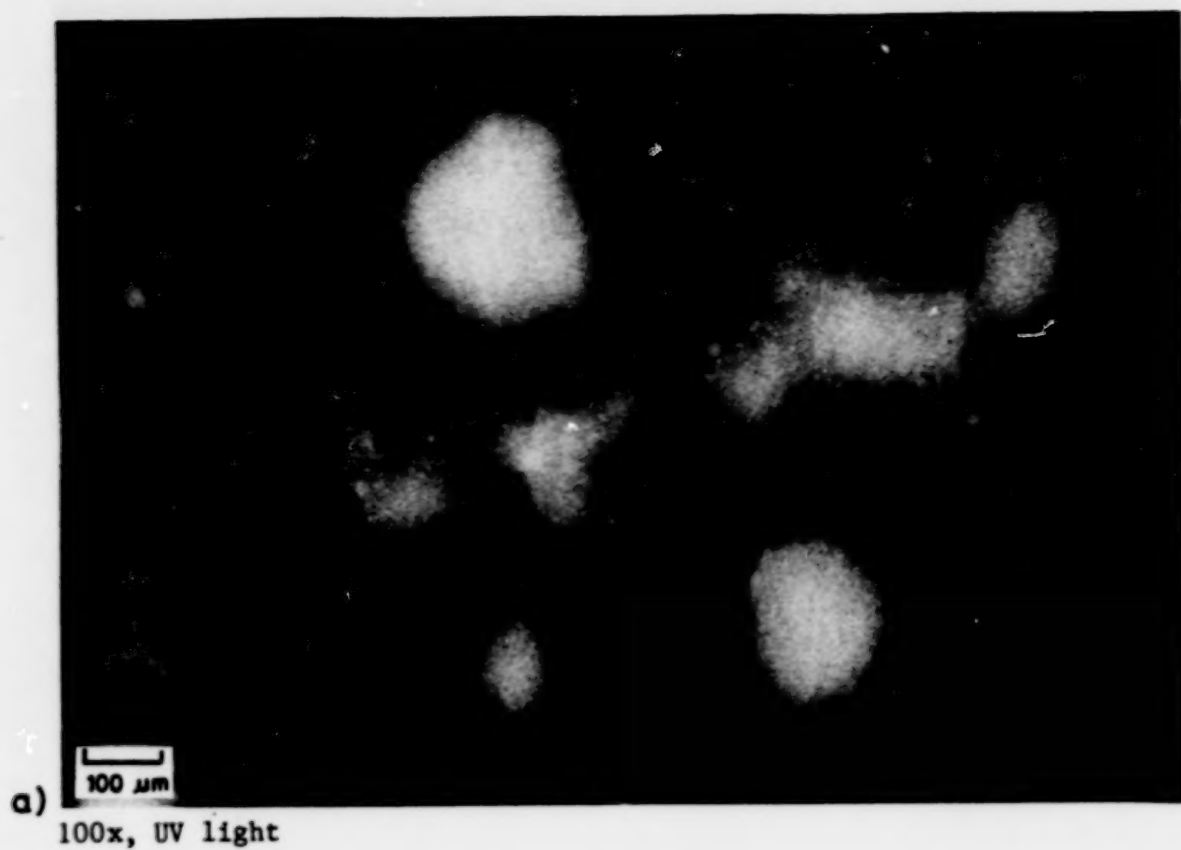
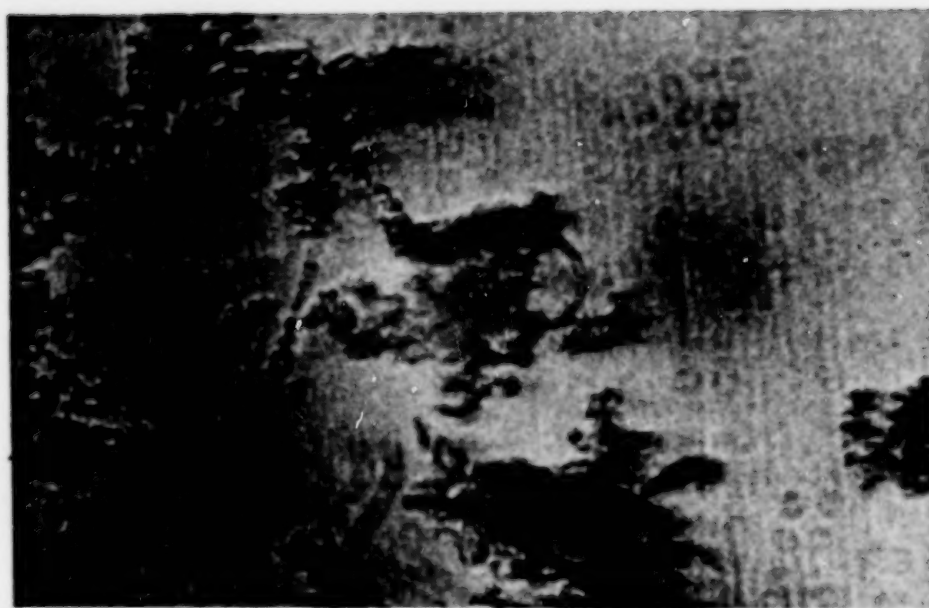


FIGURE IV. 36 Oil-SPM experiment C109 $t_m = 20$ min.
Micrograph of oiled sediment



a)
200x, UV light

100 μ m



b)
200x, UV + visible light

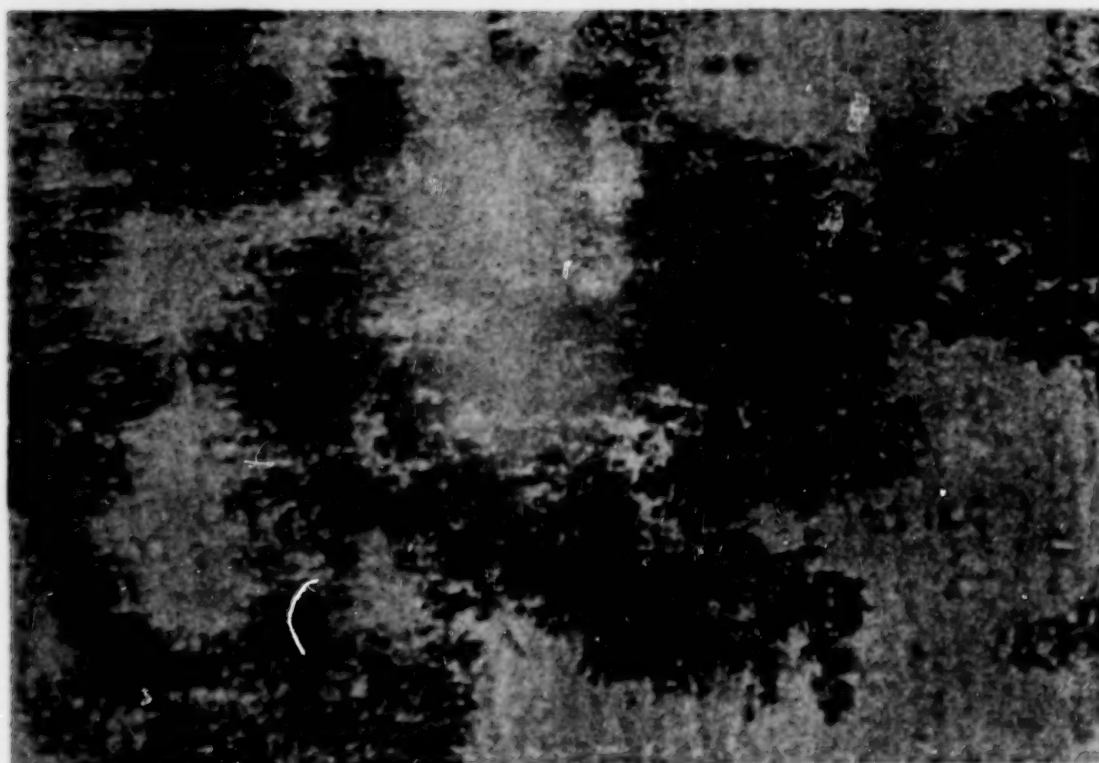
FIGURE IV. 37 Oil-SPM experiment C102 $t_m = 20$ min.

Micrograph of oiled sediment



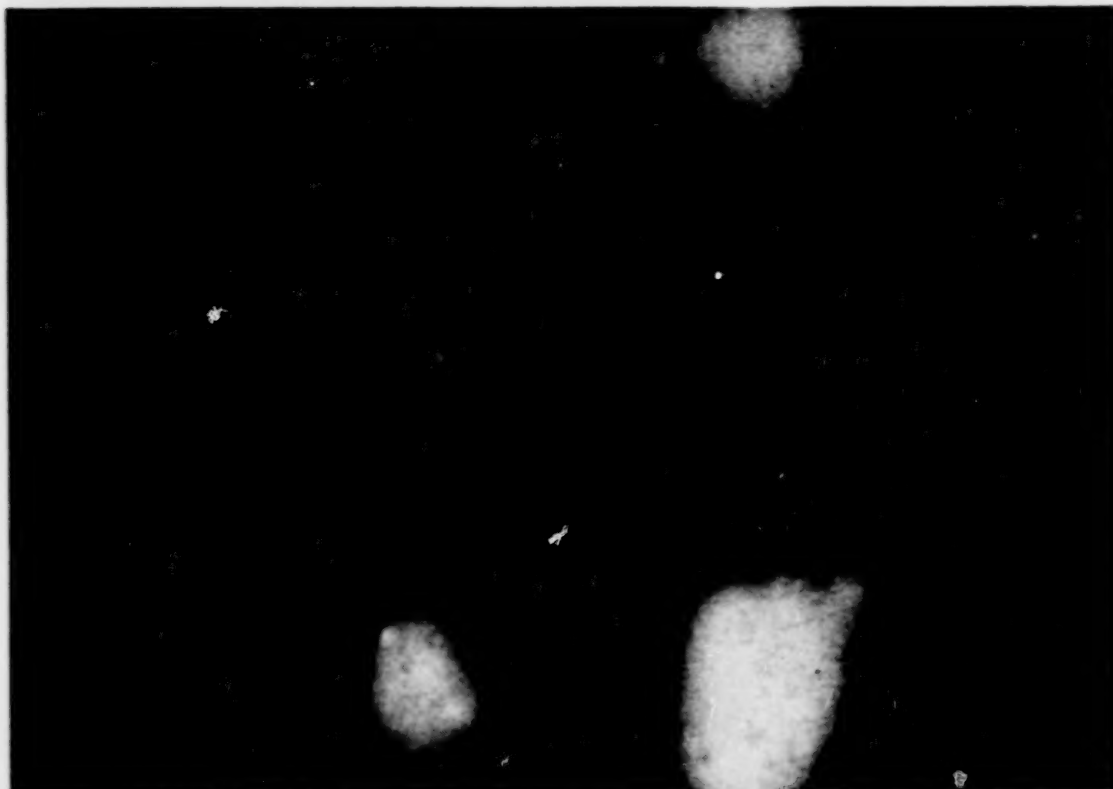
a)
200x, UV light

100 μ m



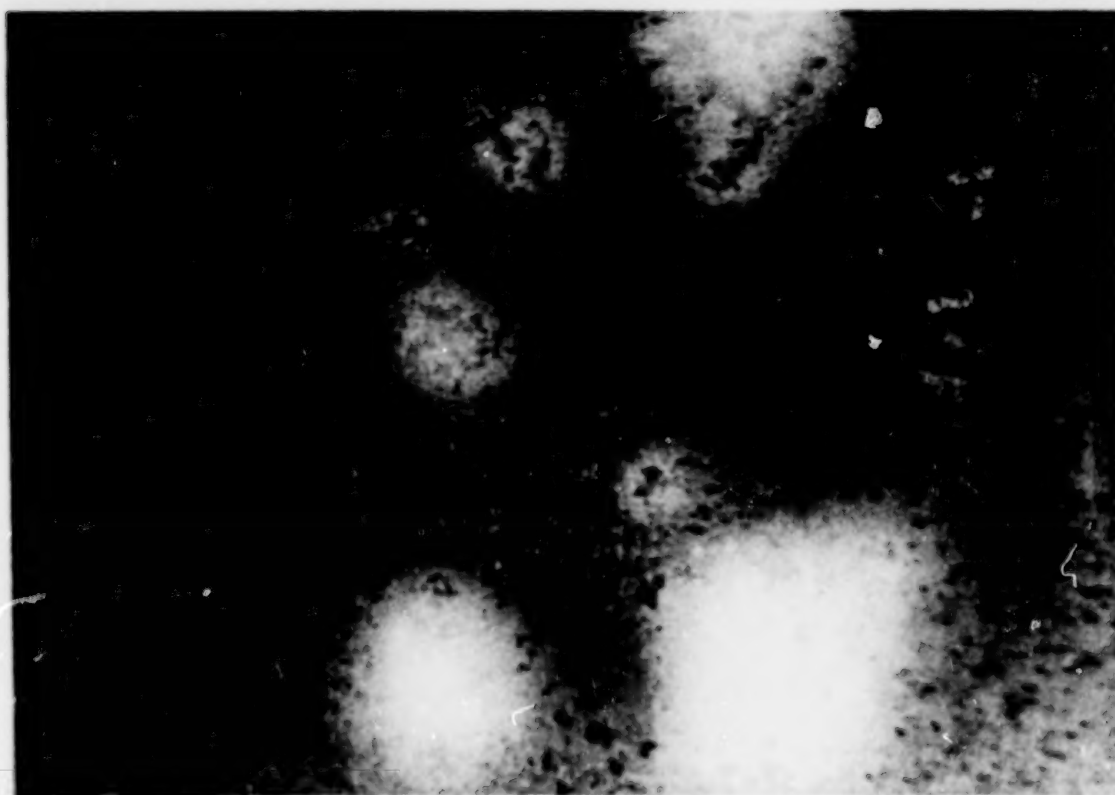
b)
200x, UV + visible light

FIGURE IV. 38 Oil-SPM experiment C102 $t_m = 180$ min.
Micrograph of oiled sediment



a) 100x, UV light

100 μm



b) 100x, UV + visible light

FIGURE IV. 39 Oil-SPM experiment C123 $t_m = 20$ min.

Micrograph of oiled sediment



a) 200x, visible light

100 μm



b) 200x, UV light

FIGURE IV.40 Oil-SPM experiment C123 $t_m = 20$ min.
Micrograph of oiled sediment

a) 100x, UV light



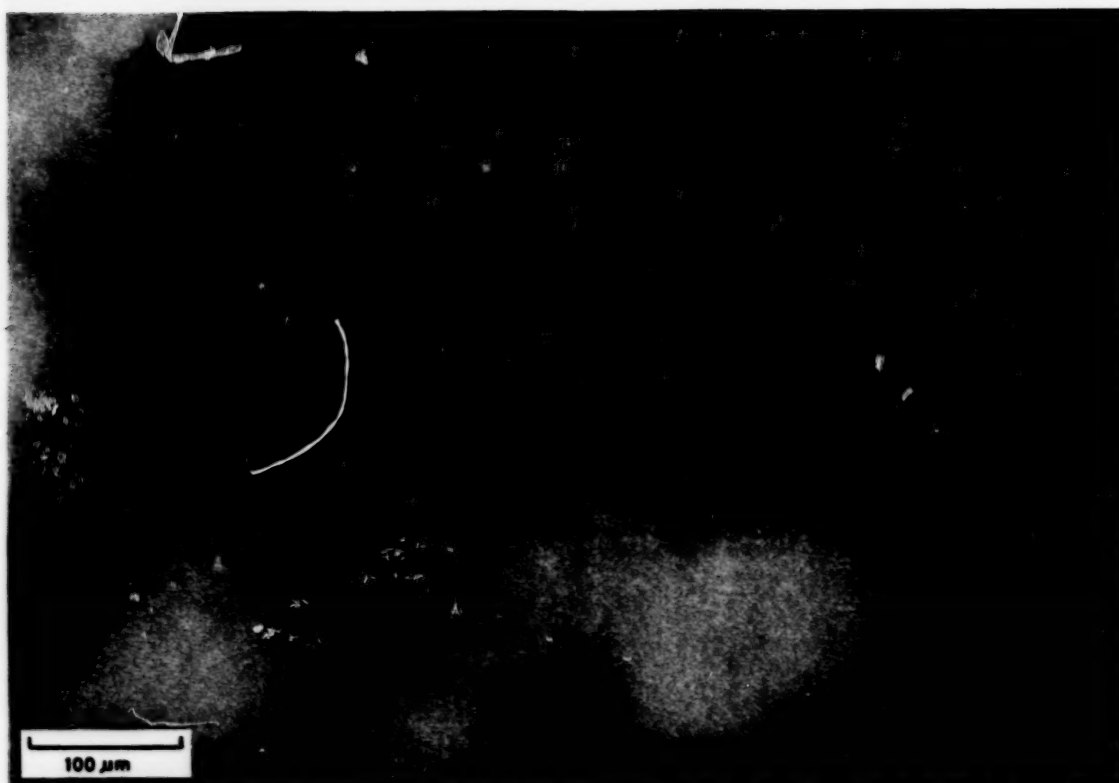
100 μ m

b) 100x, UV + visible light



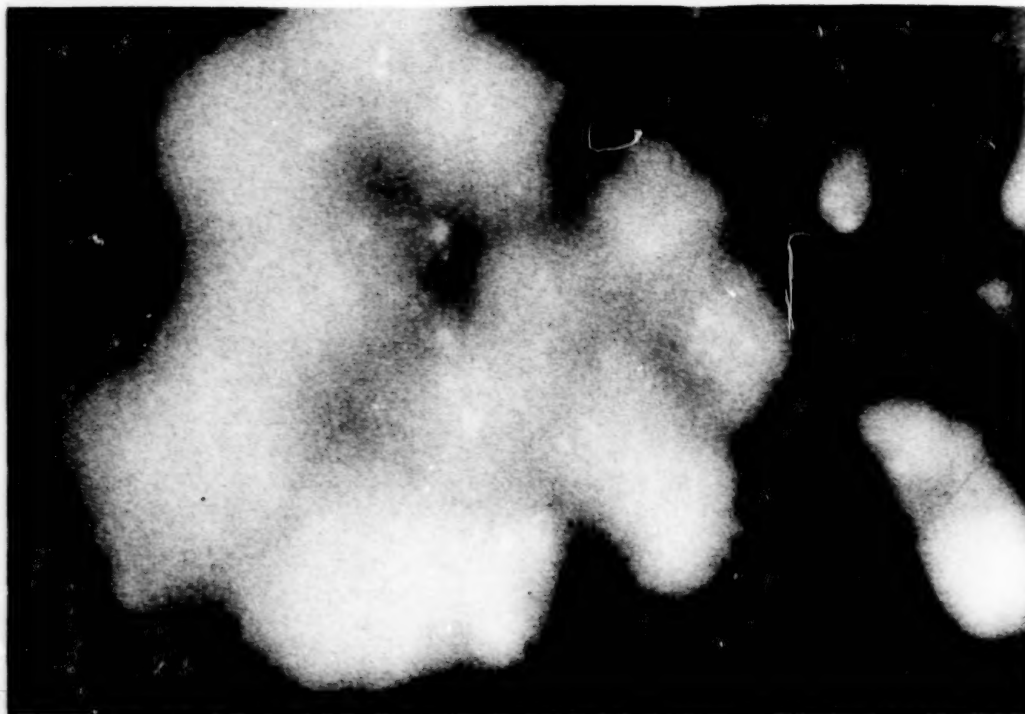
FIGURE IV.41 Oil-SPM experiment C123 $t_m = 60$ min.

Micrograph of oiled sediment



200x, UV light

FIGURE IV.42 Oil-SPM experiment C123 $t_m = 60$ min.
Micrograph of oiled sediment



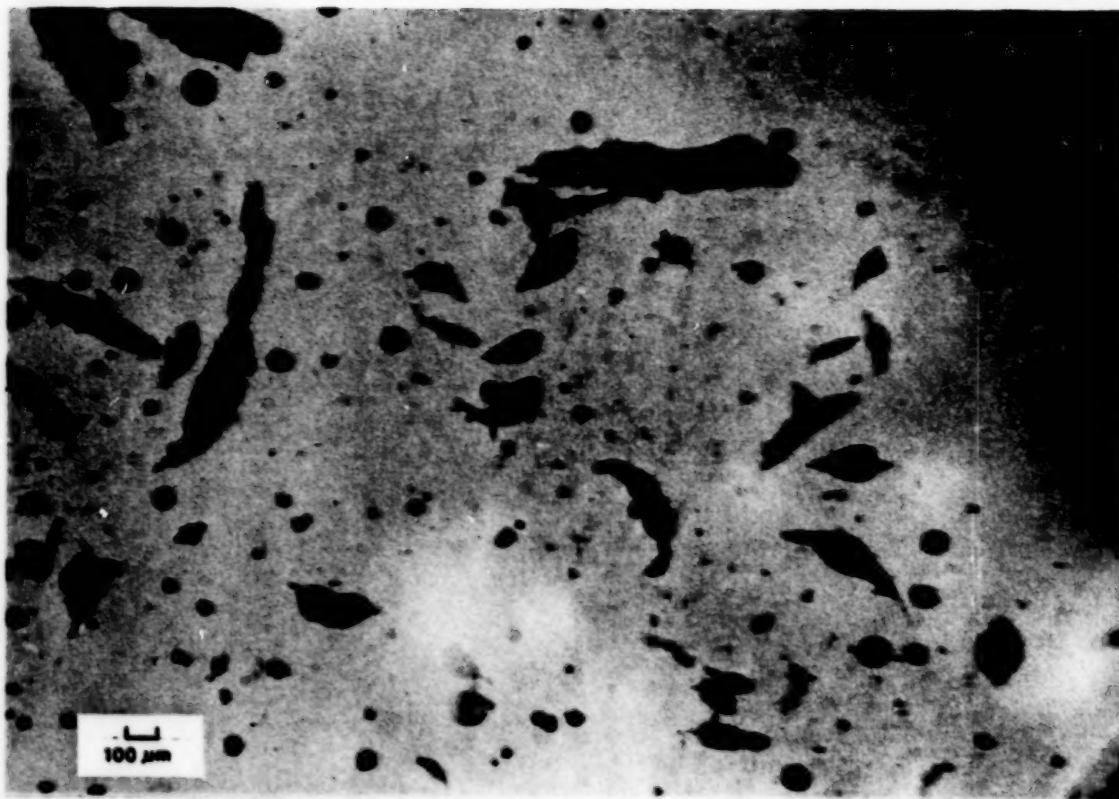
a) 200x, UV light

100 μm



b) 200x, visible light

FIGURE IV.43 Oil-SPM experiment C123 $t_m = 180$ min.
Micrograph of oiled sediment



40x

FIGURE IV. 44 Oil-SPM experiment C128A $t_m = 50$ hrs
Micrograph of buoyant oil parcels

"negatively-buoyant" oil-SPM agglomerates was in agreement with the less-coated buoyant droplets and the smaller flocs to be expected in experiments with lower SPM concentration.

Almost all oiled-sediment samples of the experiments C125, C126 and C127 were poured into shallow sample cells with sedimentation depths of only 5 mm. (See Figure A.16b)

- b) The experiments C105, C88, C103 and C106 compared the conditions with different SPM concentration, increasing from 7.5 ppm in C105, 15 ppm in C88, 30 ppm in C103 to 75 ppm in C106. Oil type (PB₃), SPM type (Waddensea silt), oil concentration (100 ppm) and turbulence level ($\epsilon = 440 \text{ J/s m}^3$) were equal in the experiments. All samples were poured into the 0.6 litre bottles with a sedimentation depth of 250 mm. Photographs of C106 oiled-sediment samples, with $t_m = 20, 60$ and 180 minutes, are shown in Figures IV.33, IV.34 and IV.35 respectively. There was no evidence of decreasing maximum droplet size in the oiled sediment for experiments with decreasing SPM concentration, in contradiction with the preceding series of experiments C125, C126 and C127. Although many conditions were different in the two series of experiments (oil weathering state, SPM type, turbulence level, and oil concentration) it is most likely that the contradiction was due to the collection of the samples in different holders, i.e. small sample cells (C125, C126, C127) and large bottles (C105, C88, C103, C106). The large sedimentation depth (250 mm) in the bottles led to relative large flocs for all SPM concentrations in which, apparently, large droplets in the order of $d_{\max} = 50 \mu\text{m}$ were captured.
- c) The micrographs in Figure IV.19, experiment C125 with PB₀, and Figure IV.30, experiment C124 with PB₃, can be used to compare the SPM-coated buoyant oil droplets for different weathering state of PB oil in similar experimental conditions. The oil droplets in experiment C124, with PB₃ looked more heavily coated. It is noted that the oil-SPM weight ratio in the oiled sediment (see Table IV.1) was higher for experiment C124 than for experiment C125. Apparently, the oil-SPM interaction was more intensive for PB₃ than with PB₀.

- d) The Figures IV.31 through IV.43 show micrographs of oiled sediment in samples taken in many different experiments and with different interaction times t_m .

The Figures IV.31b and IV.32b give a good indication of the relatively small floc sizes for kaolinite as compared with the flocs formed by Waddensea particulate matter. Waddensea flocs are shown in Figures IV.33 to IV.35 and Figures IV.37 to IV.43.

The sizes of the largest oil droplets encapsulated in the sediment did not change very much in the different experiments. d_{max} was observed to be 50, 60 or 70 μm (see also Table IV.3). Smaller maximum droplet sizes, $d_{max} = 40 \mu m$ and $d_{max} = 20 \mu m$, were found in the experiments C105 and C127, where the low SPM concentration led to very small flocs in the sediment.

In most samples, the floc sizes were large enough to capture oil droplets with sizes of about 60 μm while still being negatively-buoyant. It was observed that the larger Waddensea silt flocs did not capture larger oil droplets than the smaller kaolinite flocs. This can be explained by the assumption that the large Waddensea silt flocs were formed in the sample bottles in course of time after resurfacing of the biggest oil droplets.

Droplets of the biggest size class, $d_{50} = 60 \mu m$, are shown in Figure IV.31 (in the centre), Figure IV.32 (near the left edge), and Figure IV.41 (left part). Figure IV.40 is the best example showing many small oil droplets in the size class of $d_0 = 5 \mu m$.

- e) Figure IV.44 shows the buoyant oil parcels of the stirred beaker experiment C128A, with PB₃ oil. The sample was taken at $t_m = 50$ hrs. Clearly, emulsification did take place. The micrograph shows buoyant oil droplets as well as oil filaments. Oil droplets and oil filaments were also observed in the negatively buoyant oiled sediment of the sample withdrawn at $t_m = 50$ hrs. No visible emulsification occurred in experiment C128B with Ekofisk oil, or in any case, eventual emulsification did not lead to other than spherical oil particles.

IV.6.2 Results

The results obtained from visual microscopy are:

- a) Naked-eye visual observation of sedimented matter, phase III, in a "blank" kaolinite experiment without oil, indicated relatively small white flocs. A similar experiment with oil showed grey sediment consisting of larger flocs.

Note: LBPS measurements did not demonstrate different particle size distributions in the grid column for experiments with and without oil, see Section IV.3, page 137. However, the LBPS measurements dealt with particles in a turbulent environment, while the previous result dealt with samples removed from the turbulent grid column and left for many hours in a stationary position where additional flocculation occurred due to Brownian motion and differential settling.

- b) Microscopic observation of sedimented matter indicated only discrete oil droplets incorporated in silt flocs. No fluorescence of silt particles was observed. This means that no substantial amount of oil was adsorbed as a film on the particle surface. (The minimum layer thickness of oil on a particle surface that could be observed is not known, but was in any case smaller than $1\text{ }\mu\text{m}$, because the smallest discrete oil droplets observed were about $1\text{ }\mu\text{m}$).
- c) The size distribution of the oil droplets incorporated in sedimented silt flocs was not significantly variable in experiments with different oil types (PB_0 , PB_3 , Ekofisk), silt types (kaolinite and Waddensea silt) and turbulence level ($\epsilon = 440$ and 3500 J/s m^3). Almost all droplets in the oiled sediments had sizes according to $1\text{ }\mu\text{m} \leq d_o \leq 60\text{ }\mu\text{m}$. The size of the largest oil droplets in the sediment was always $d_{\text{max}} = 60\text{ }\mu\text{m}$ except for conditions in the column (low SPM concentration) and/or sampling device (low SPM concentration, small sedimentation depth) that seriously hampered the formation of silt flocs.

- d) Buoyant oil droplets in the experiments were more or less heavily coated with SPM particles. The buoyant droplet sizes covered the entire range of droplet sizes obtained in experiments without SPM, from $d_0 = 1 \mu\text{m}$ to d_{max} of the order of magnitude of $1000 \mu\text{m}$. Remarkable differences in oil droplet coating was not observed for different experiments with respect to oil type, SPM type, turbulence level and interaction time. The coating was less in experiments with low SPM concentration.
- e) The rough quantitative observations on the occurrence of different agglomerates did not indicate any tendency other than what might be expected from the occurrence of separate oil droplets and SPM particles. All observations fell in a continuous range from "oil droplets incorporated in a SPM floc", to "oil droplet coated with SPM particles". The ratio of oil and SPM in an agglomerate determined the buoyant or non-buoyant behaviour of the agglomerate; this probably resulted in a maximum oil droplet size in the non-buoyant oiled sediment. (See conclusion c).
- f) Emulsification of PB₃ oil was observed in the beaker experiment C128A, at $t = 5$ hrs and $t = 50$ hrs. The oil droplets were no longer spherical but had different shapes as observed in surface oil (phase I) as well as in oiled sediment (phase III).

IV.7 Discussion

The purpose of the oil-SPM interaction experiments was to obtain data on the oil-SPM agglomerates, in particular with respect to buoyancy and floc size. These parameters are of great influence on the vertical motion of the oiled particles in a turbulent ambience and, ultimately, on the sedimentation on the sea floor.

The grid column enabled the simulation of real ocean conditions as far as the energy level and structure of the small turbulent eddies are concerned, and consequently, a proper simulation was obtained of the

interaction between oil and SPM. The interaction takes place by collisions. In the phenomena under investigation, the collisions between oil droplets and silt particles, and the mutual silt particle collisions are of particular interest. Collisions in the grid column are due to the following processes:

- a) shear caused by turbulence. The shear is mainly due to the small-scale turbulent eddies, properly modelled in the grid column.
- b) Brownian motion.
- c) differential setting. (Collisions due to different fall and rise velocities of the particles).

In a turbulent ambience, the turbulence is generally the most important phenomenon for oil-SPM interaction, not only with respect to the colliding of particles, but also to the mechanisms regulating the maximum size of the agglomerates and the maximum size of the oil droplets.

Proper modelling of field conditions for oil-SPM interaction took place in the grid column. However, the limited length of the column (4 metres) prevented the performance of experiments with turbulence levels considerably lower than 440 J/s m^3 . Low turbulence levels mean low diffusion rates and, therefore, rapid resurfacing of the oil droplets, even enhanced by the fact that the mean droplet sizes are relatively large in the case of low turbulence. It is not expected that turbulence levels less than 440 J/s m^3 effect the results of the experiments (performed with $e = 440$ and $e = 3500 \text{ J/s m}^3$) else than differences in degree with respect to oil - SPM interaction. The tendency of smaller values of ϕ/s in oiled sediment for lower turbulence level, shown in Figure IV.14, will be continued because of a continuing reduction of the number of small oil droplets and the oil - SPM collision probabilities. (It is a result of this study that small oil droplets down to $d_0 = 1 \mu\text{m}$, are generated by break-up of large droplets even in conditions with low turbulence energy, but the number of small droplets decreases with decreasing turbulence level).

The effect of proper modelling of field conditions for oil-SPM interaction in the grid column could be distorted occasionally by difficulties with

the sampling procedure. The set-up of the experiments and in particular the chemical analysis (determination of oil/silt ratio and oil composition in the various phases) required a oil and SPM concentration in the column in the order of magnitude of 10 ppm or more and a sample volume in the order of magnitude of 1 litre. The consideration of the collision probabilities in sample cells, see Appendix A.4, indicated a high collision probability in the cells due to differential settling. Another important conclusion, obtained from the measurements in the preceding sections, was the sometimes considerable oil adsorption obtained after a short interaction time of one minute in the column. Consequently, it is not clear whether the oil-SPM interaction observed from samples, is due to interaction in the column or in the sample cell, or both. In any case, microscopic observation of sedimented matter from different sample cells showed different floc sizes. The flocs in the sample cell with a height of 5 mm were considerably smaller than the generally very large agglomerates from the 250 mm high bottles because of the difference in collision probability. (See also the many micrographs in the Figures IV.17 to IV.44; samples in the 5 mm cell are indicated by c in Table IV.3, and samples from the 250 mm bottles by b). Chemical analysis required large sample cells for quantitative data, while the small cells were only used for the more or less qualitative microscopic observation. Consequently, the results obtained from the grid column experiments on oil-SPM interaction have a mainly qualitative value with respect to the influence of various parameters on the interaction, due to the combined interaction processes in the grid column (simulation of sea conditions) and in the sample cells.

It was decided to abandon the attempt to conduct experiments on oil-SPM interaction under the influence of breaking waves in a laboratory flume. One of the reasons was the expected lack of proper quantitative data to be obtained because the same problems would arise with respect to the required oil-SPM concentration and the sampling procedure as for the grid column. A second reason concerned the experiments in the flume itself. It would be necessary to continue the interaction conditions (and therefore also the breaking wave generation) for a long time of, say, at least 20 minutes (conclusion from the grid column experiments). Preliminary

experiments on oil break-up in a flume with successive breaking waves over several minutes (see Section V.8), demonstrated the impossibility of relating the measured data to a well-defined set of external parameters (e.g., oil layer thickness, oil viscosity) because of fast changing conditions during an experiment. The changing conditions were due, among other factors, to fast emulsification of the surface oil slick, and longitudinal circulations in the flume generated by the waves.

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V. SMALL-SCALE EXPERIMENTS ON OIL DISPERSION BY BREAKING WAVES

V.1 Introduction

The turbulence in the ocean is an important factor in various processes affecting the dispersion of oil. The initial break-up and submerging of the coherent oil surface slick as well as the secondary break-up of the oil parcels into smaller droplets is dependent on the turbulence structure, especially near the water surface. Moreover, turbulence plays an important role in the vertical diffusion of oil droplets into the water column.

The turbulence in the surface layer of the sea is generated by overall (tidal) sea currents, wind-drift currents and waves. The wind-drift currents and waves in turn are generated by the wind. It is generally believed that substantial dispersion of surface oil requires the presence of breaking waves. It is not known if the presence of breaking waves is essential to obtain any dispersion in field conditions. Probably, the stretching and contracting of the oil surface layer by waves can also lead to some dispersion, but in any case small-scale laboratory experiments with only non-breaking waves never did lead to measurable dispersion of oil.

This section describes the simulation of oil dispersion in a small-scale laboratory flume, the "Oil Flume". The dispersion is due to turbulence generated by a breaking wave. The experiments were conducted to obtain experimental data on the following parameters:

- a) entrainment rate of surface oil into the water column by breaking waves, or how much oil is entrained from the water surface by a single breaking wave,
- b) depth of intrusion of oil in the water column, due to a breaking wave,
- c) oil droplet size distribution in the water column.

As regards item c, the influence of turbulence on the droplet size distribution in different conditions was investigated in the grid column.

(Section III.) Turbulence levels of the grid column experiments on oil dispersion were of the same order of magnitude as in field circumstances. Consequently, scaling of the oil break-up processes did not take place in the grid column experiments. In the flume experiments, the diffusion and dispersion processes were generated by the turbulent structure of a small-scale breaking wave (wave height is of the order of 0.2 m) while the oil parameters that influence these processes (interfacial tension, viscosity, density) were not scaled. Therefore, the results of the flume measurements must be translated to field conditions taking into account the effects of scaling of the turbulence structure. The small-scale Oil Flume experiments were compared with large-scale (almost full-scale) experiments in the Delta Flume in closely similar conditions to facilitate the laboratory-field translation. The Delta Flume experiments are discussed in Section VI.

V.2 Experimental Set-up

The flume contained salt water, $S = 30 \text{ }^{\circ}/\text{oo}$, $\rho_w = 1025 \text{ kg/m}^3$. The water depth was $h = 0.43 \text{ m}$ in all experiments. The Oil Flume and the measurement equipment are described extensively in Appendix A.1.2.

Entrainment and break-up of surface oil into the water column took place by breaking waves. This was generally performed in the experiments by the traversing of a wave train with a single breaking wave through the coherent surface oil layer. Seven different types of wave trains were generated by the wave board. The seven wave trains have different energy dissipations and different orbital movements, the latter being weak or strong at the flume bottom.

The oil surface layers were formed by pouring oil onto the water surface in the flume. (See Figure V.1). The oil slicks covered the total width (0.5 m), while the slick lengths were generally several metres. In order to obtain an oil film with the layer thickness $h_o = 0.6 \text{ mm}$, a volume of 0.6 litre of oil was poured onto the water surface in between two barriers across the flume. The barriers were separated by 0.1 metre. Gravitational



FIGURE V.1 Oil surface layer in the flume

spreading of the oil took place in between the barriers, with a layer thickness $h_o = 6$ mm. Subsequently, the barriers were displaced slowly until a separation of 2 metres was obtained, while the oil layer was forced to stretch over the entire surface. Visual observation of the transparency of the oil films indicated that the thin and thick parts of the film did not differ more than a factor two, that is $h_o = 0.4$ to 0.8 mm. The barriers were removed prior to the passage of the waves. The breaking of the waves took place completely within the oil slick, the waves broke over a length between 0.7 and 2.5 m. Figure V.2a shows the passage of the breaking wave through the oil layer. The initial intrusion of oil droplets in the water column is shown in Figure V.2b, the picture was taken within a few seconds after the breaking wave passage.

The dispersion of oil was surveyed by acquiring the following data:

- a) Oil droplet size distributions $d_o(f)$ at different vertical positions (depth below the water surface) and different times after the breaking wave event. Two series of measurements were performed with the following methods of $d_o(f)$ determination:

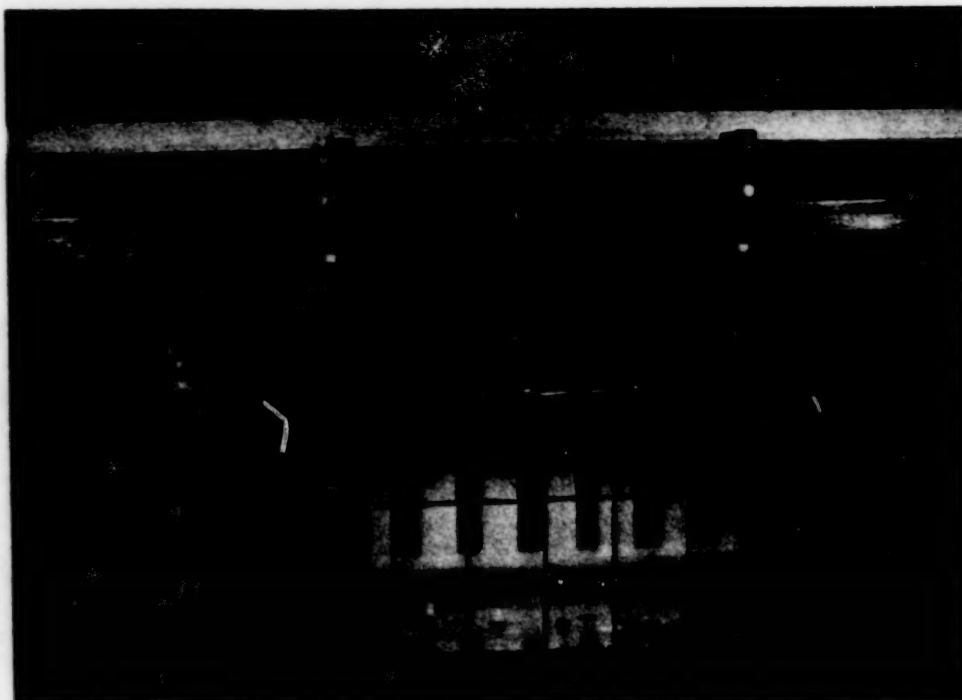
- al) Laser-Beam Particle Sizer (LBPS). The LBPS is described in Appendix A.2.1. This electronic equipment for particle size determination was used in the first series of experiments in the Oil Flume. The optical system with focal length of 0.6 m enabled in-situ measurement of $d_o(f)$. This means that the laser beam crossed the width of the flume using the flume itself as the sample cell. This optical system could measure particle sizes in the range from 11.5 to $1130 \mu\text{m}$.

The $d_o(f)$ measurements were executed at four depths shown in Figure V.3. Two measurements were carried out simultaneously by using two particle sizers, indicated by A and B in Figure V.3. The experiments were performed twice with fresh oil layers to obtain the first (I) and second set (II) of $d_o(f)$ measurements.

Figure V.4 shows a typical example of LBPS data with $d_o(f)$ as a function of time t_m after the breaking wave event. The $d_o(f)$ curves clearly show the disappearing of large oil droplets in

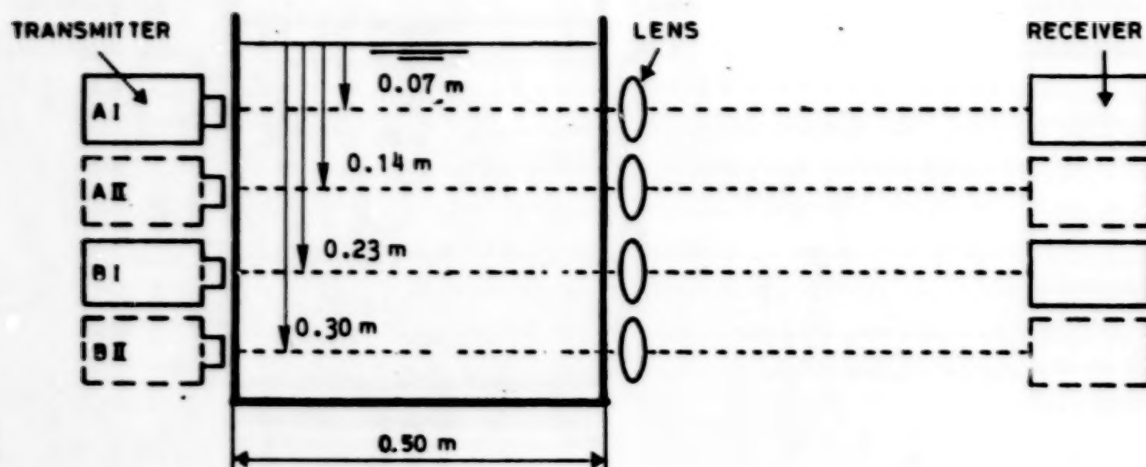


a) passage of breaking wave

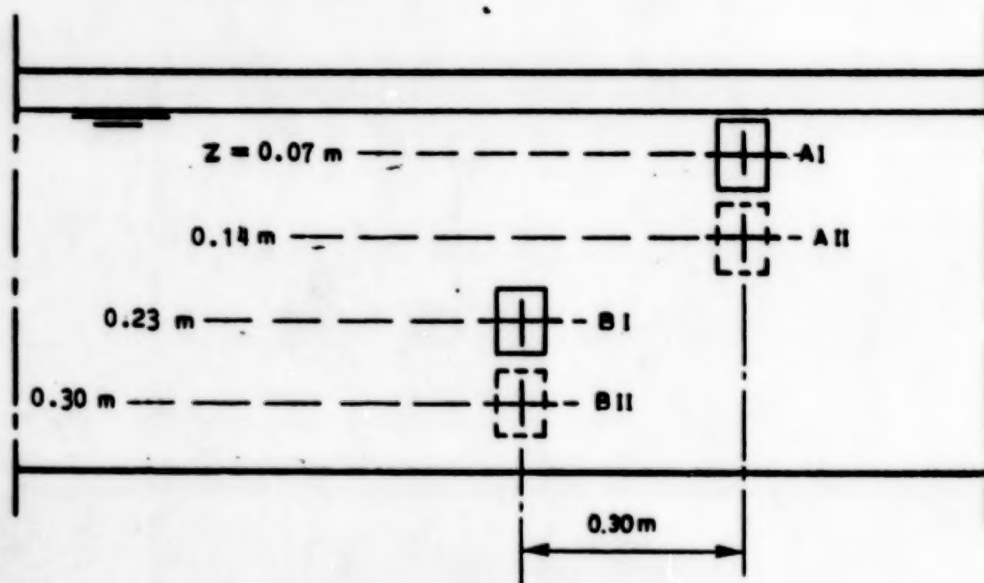


b) initial intrusion of oil droplets

FIGURE V. 2 Dispersion of oil due to breaking wave



a) cross-section view



b) side view

FIGURE V. 3 In-situ $d_o(f)$ measurement with the LBPS in the oil flume

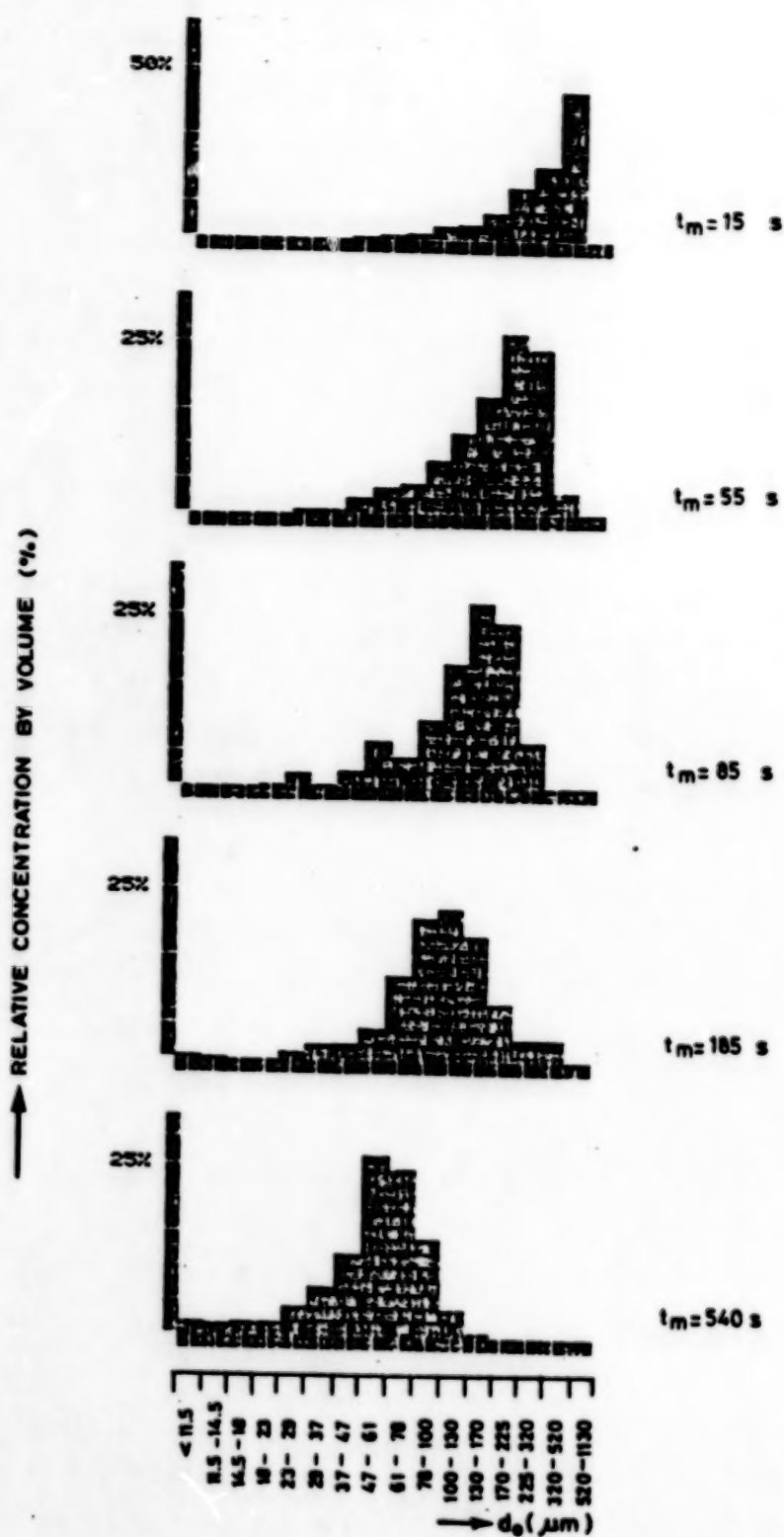


FIGURE V.4 Example of LBPS data at various time t_m after wave breaking

course of time due to resurfacing.

- a2) Visual microscopy. A second series of experiments in the Oil Flume made use of the samplers described in Appendix A.2.3 to withdraw water-and-oil samples at different depths and times t_m . Determination of $d_o(f)$ in the samples took place by microscopic observation with the fluorescence apparatus described in Appendix A.2.2, especially for droplets in the range $d_o = 3-200 \mu m$. Oil droplets in the range $d_o = 100 - 2000 \mu m$ were surveyed by direct photography of the oil droplets surfaced to the flat top glass of the sampler. Typical observations are shown in Figure V.5 with an example of direct photography and a photograph taken through the microscope.

The determination of $d_o(f)$ took place by visual scanning and counting.

The series of experiments with the LBPS was followed by a second series with the samplers and visual microscopy because the LBPS appeared unsuitable for detection of small oil droplets if a considerable "background" of large droplets is present. This is shown well in Figure V.4 where no oil droplets smaller than $37 \mu m$ are detected at $t_m = 15 s$. (See also Appendix A.2.1).

- b) Oil concentration. Oil-water samples of 0.6 litre were withdrawn by the sampling nozzles (see Figure A.7) at various depths and times t_m after the breaking event. The oil concentration was measured by infra-red spectroscopy.
- c) Intrusion of droplets. This was determined by taking photographs at various times t_m after the breaking event. Figures V.6 and V.7 show examples. The initial intrusion by oil droplets can be seen in Figure V.6. The pictures show the break-up of the oil surface layer and the intrusion of oil droplets in the water mass in the first second after passage of the breaking wave.

The long-term horizontal and vertical diffusion is difficult to survey with oil droplet pictures. Consequently, for purpose of illustration, Figure V.7 shows pictures of the diffusion of dye during twenty

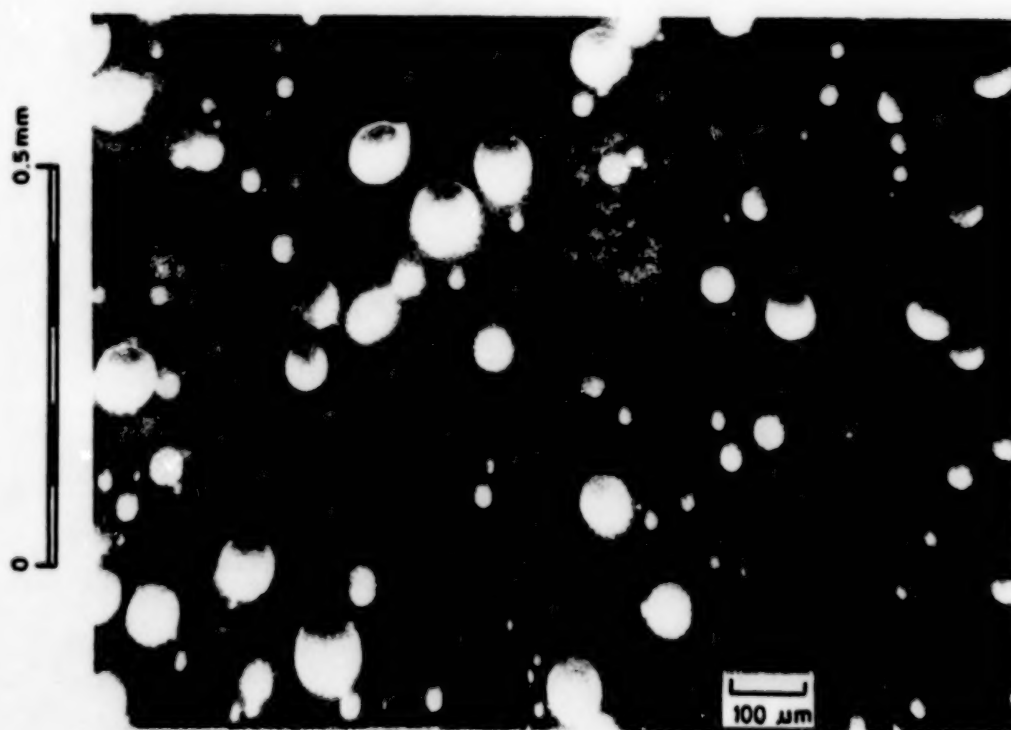
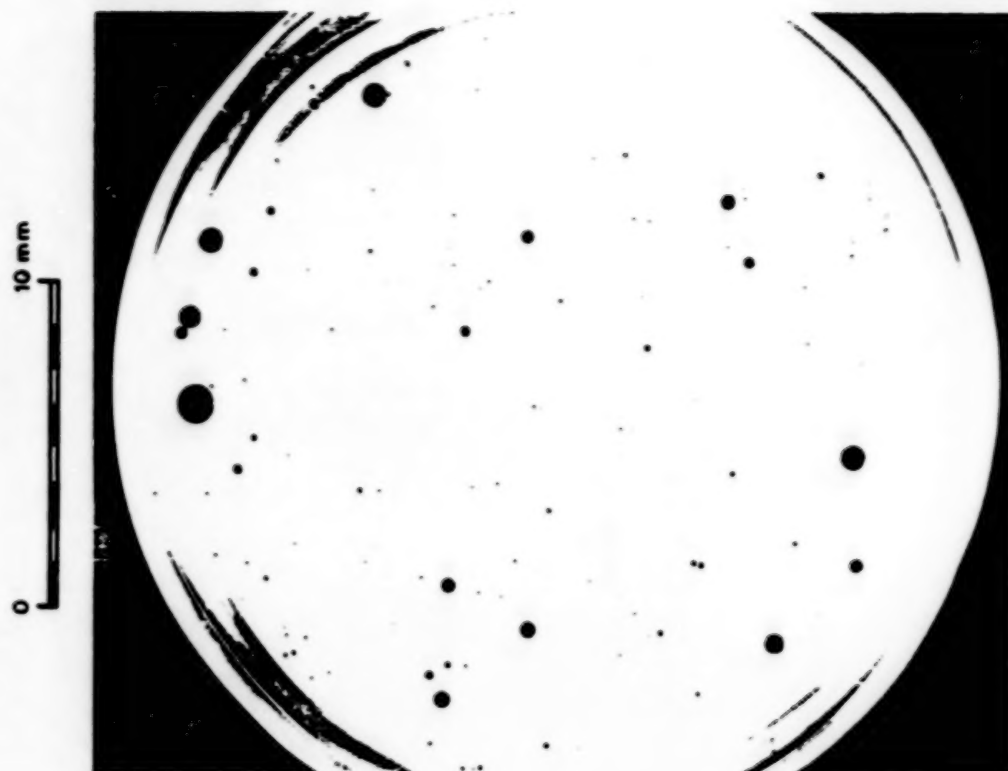


FIGURE V. 5 Photographic and microscopic observation of oil droplets in the sampling device

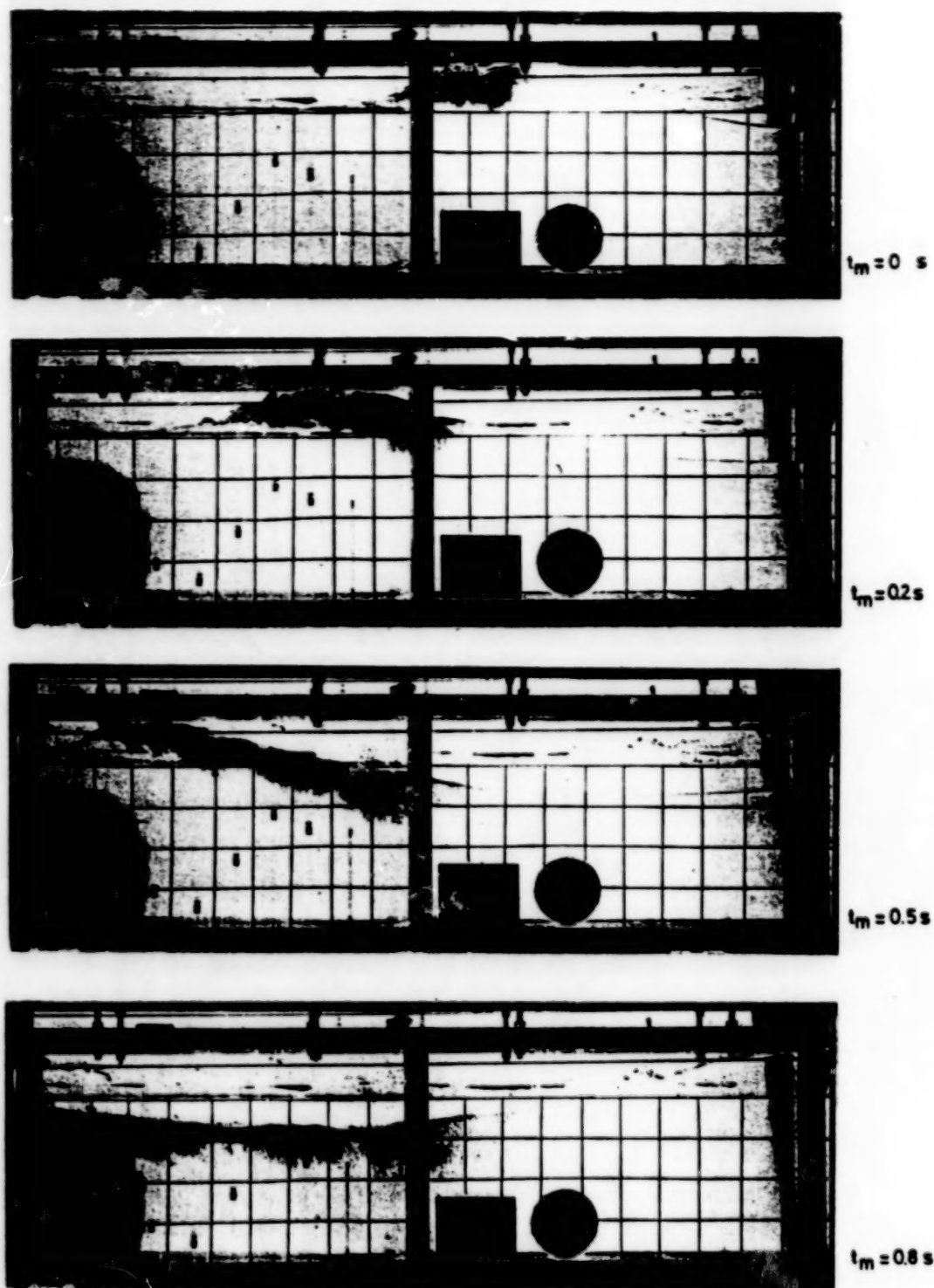
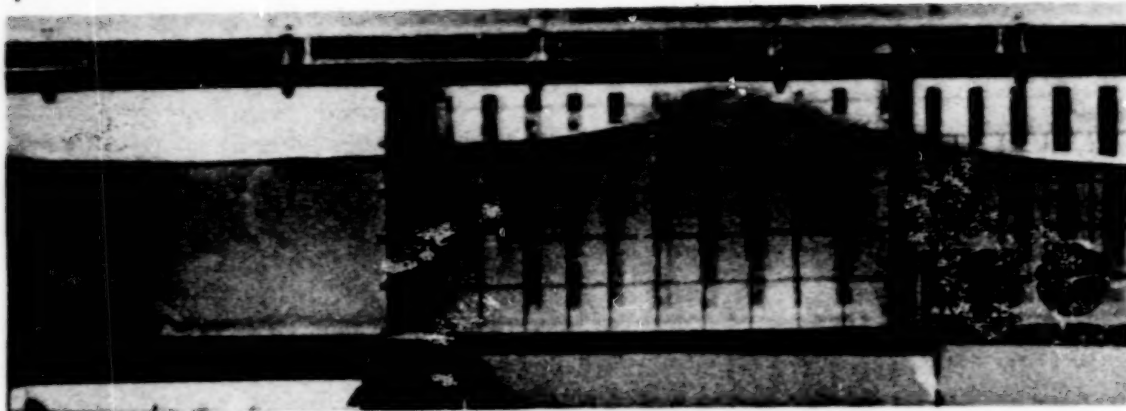
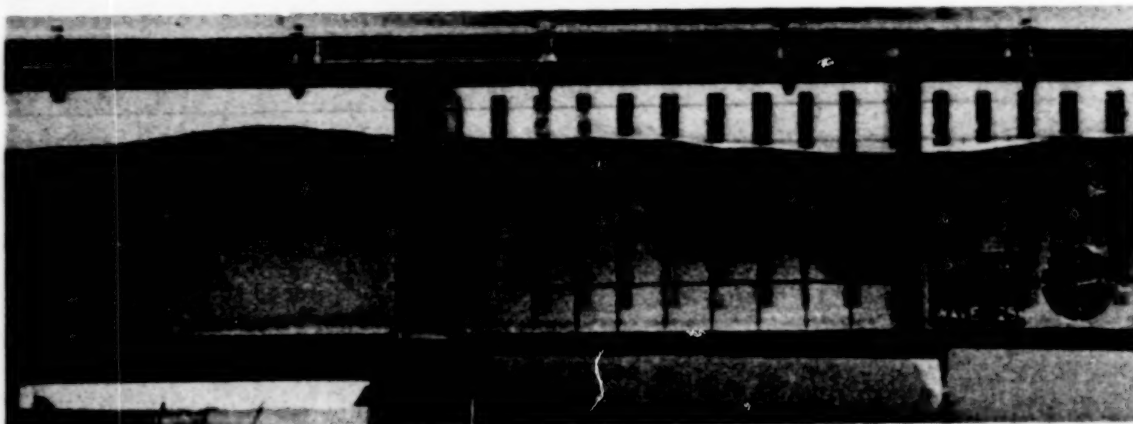


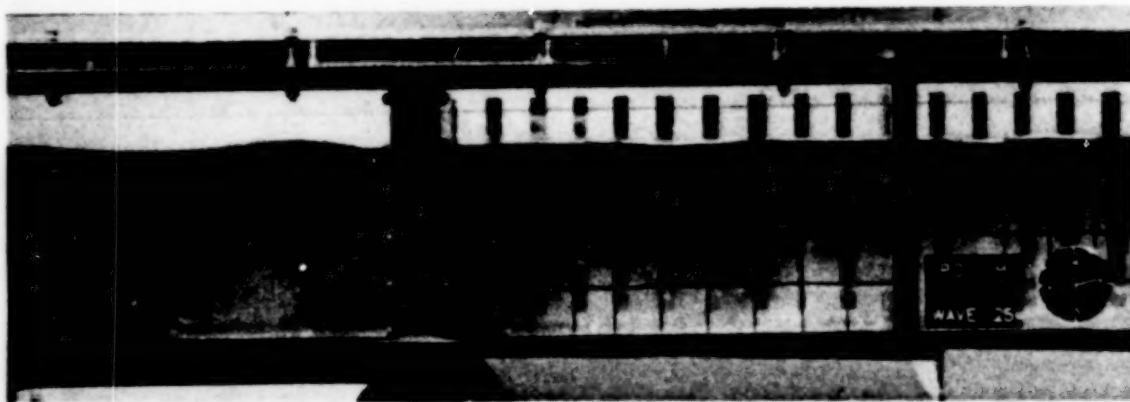
FIGURE V.6 Intrusion of oil droplets by breaking wave



a) $t_m = 0$



b) $t_m = 5 \text{ s}$



c) $t_m = 20 \text{ s}$

FIGURE V.7 Intrusion and diffusion of dye due to breaking wave
(wave 2)

seconds after the breaking wave passage. The dye was sprayed on the water surface just before the wave passage, while no oil was used. (It was checked empirically whether the oil films would have a damping effect on the breaking waves and, therefore, would differ from the inertial dye film. The horizontal and vertical spread of oil droplet clouds were equal for all applied film thicknesses. Consequently, the dye tracer will satisfactorily simulate the spreading of the small droplets with negligible buoyancy).

Oil Flume experiments were executed with different values of the following parameters:

- a) wave period T_w . The mean values of T_w for the different wave trains were $T_w = 1.3, 1.25, 1.2, 1.1, 1.0, 0.9$ and 0.8 s. The wave trains contained breaking waves with different energy losses and, therefore, different turbulent structures. (The wave trains are generally indicated by wave 1, 2, 3, 4, 5, 6, 7 respectively).
- b) oil type and weathering state. Prudhoe Bay crude (PB) and Ekofisk crude (Eko) were used. PB oil was applied with different weathering states: PB_0 (fresh), PB_3 and PB_{10}
- c) surface oil film thickness $h_o = 0.2 - 1.2$ mm
- d) temperature $T = 9$ °C and 16 °C
- e) number and interval of succeeding breaking waves in an experiment:
 - 1 breaking wave
 - 4 breaking waves at 15 s interval
 - 4 breaking waves at 30 s interval
 - 4 breaking waves at 60 s interval
 - 10 breaking waves at 30 s interval

V.3 Breaking Waves Characteristics

The important breaking wave parameters for oil entrainment and oil break-up are the total surface length l_b covered by the breaking wave, the energy dissipation per unit surface area D_{ba} , and the energy dissipation rate per unit volume, e . The first parameter indicates how much surface oil is involved in the dispersion process. The total energy dissipation

per unit area is probably important to the ratio of surface oil over dispersed oil and the energy dissipation rate per unit volume indicates the turbulence structure and therefore the break-up of oil droplets and the vertical diffusion of oil.

V.3.1 Theory of energy dissipation in breaking waves

The dissipated energy in a wave train with one single breaker can be derived from the energy balance for the breaker zone. Subtracting the time-integrated energy fluxes before and beyond the breaker zone leads to the following expression (see the definition sketches in Figure V.8a):

$$D_b = \int P_I dt - \int P_{II} dt \quad (V.1)$$

in which: D_b = energy dissipation per unit width (J/m)

P_I, P_{II} = energy fluxes before and beyond the
breaker zone per unit width (J/s m).

When linear wave theory is applied the energy flux P for an infinite wave train with regular waves (described by $\eta = a \sin(2\pi ft)$, with η = instantaneous surface elevation, a = wave amplitude, f = wave frequency, see Figure V.8b) can be expressed by:

$$P = E n_w c \quad (V.2)$$

in which: $E = \frac{1}{2} \rho_w g a^2$ = wave energy per unit area (J/m²)

$$n_w = \frac{1}{2} + \frac{kh}{\sinh(2kh)}$$

($n_w = \frac{1}{2}$ for deep water, $n_w = 1$ for shallow water)

c = wave crest velocity

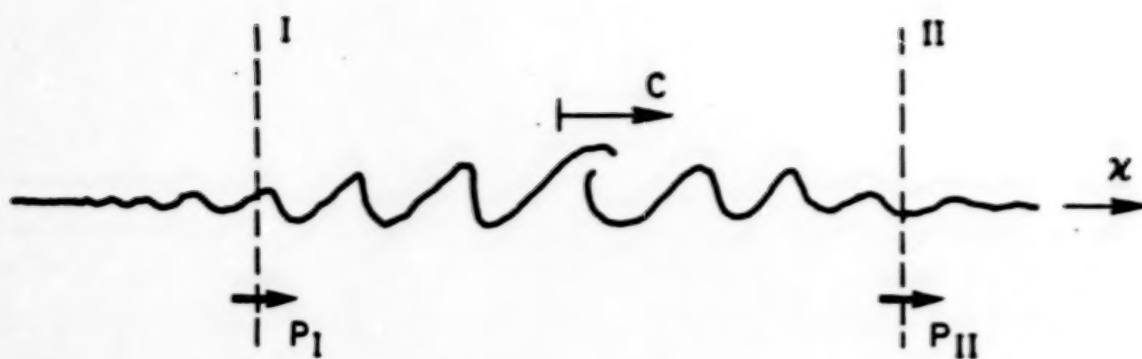
ρ_w = water density

g = gravity constant

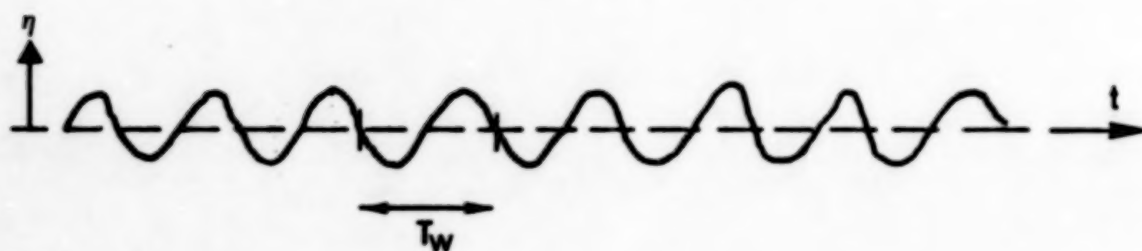
$k = 2\pi/L$ = wave number

L = wave length

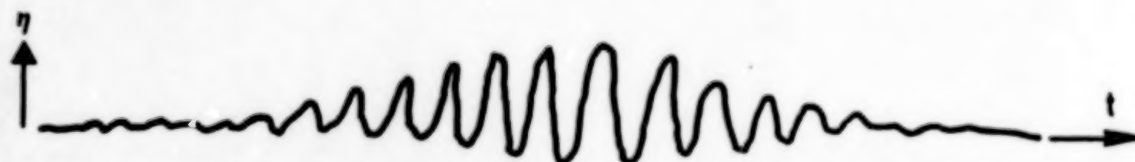
h = water depth



a) breaker zone



b) infinite wavetrain with regular waves: $\eta(t) = a \sin(2\pi f t)$



c) finite wavetrain with irregular waves: $\eta(t) = \sum_i a_i \sin(2\pi f_i t)$

FIGURE V. 8 Wave train definition sketches

Combination of (V.1) and (V.2) leads to:

$$D_b = \frac{1}{2} \rho_w g n_w c \left[\int_0^{\Delta t} a_{II}^2 dt - \int_0^{\Delta t} a_I^2 dt \right] \\ = \frac{1}{2} \rho_w g n_w c (a_I^2 - a_{II}^2) \Delta t \quad (V.3)$$

In which the subscripts I and II indicate the values of a before and beyond the breaker zone and Δt stands for the interval of time integration.

In the case of a finite wave train with irregular waves (described by $\eta(t) = \sum a_i \sin(2\pi f_i t)$, see Figure V.8c) and one single breaking wave, the energy dissipation can be expressed as:

$$D_b = \frac{1}{2} \rho_w g n_w c \left[\int_0^{\Delta t} (\sum a_i^2)_I dt - \int_0^{\Delta t} (\sum a_i^2)_{II} dt \right] \\ = \frac{1}{2} \rho_w g n_w c \left[(\sum a_i^2)_I - (\sum a_i^2)_{II} \right] \Delta t \quad (V.4)$$

The parameters n_w and c in (V.4) can be measured in the laboratory wave flumes, but the amplitudes a_i of the wave components are unknown. It is possible to calculate an "integrated power spectrum", PS (in m^2s), by time-integration of the instantaneous surface elevation $\eta(t)$ with a digital signal analyzer (Hewlett Packard, type 5420 A). PS is defined by:

$$PS = \int_0^{\Delta t} \eta^2(t) dt = \sum \frac{1}{2} a_i^2 \left[\Delta t - \frac{1}{4\pi f_i} \sin(4\pi f_i \Delta t) \right] \quad (V.5)$$

If the interval of integration, Δt , is chosen to be much larger than $\frac{1}{4\pi f_i}$, then PS is approximated by:

$$PS = \sum \frac{1}{2} a_i^2 \Delta t \quad (V.6)$$

Substitution of PS in Equation (V.4) results in an expression for the energy dissipation per unit width:

$$D_b = \rho_w g n_w c [PS_I - PS_{II}] \quad (V.7)$$

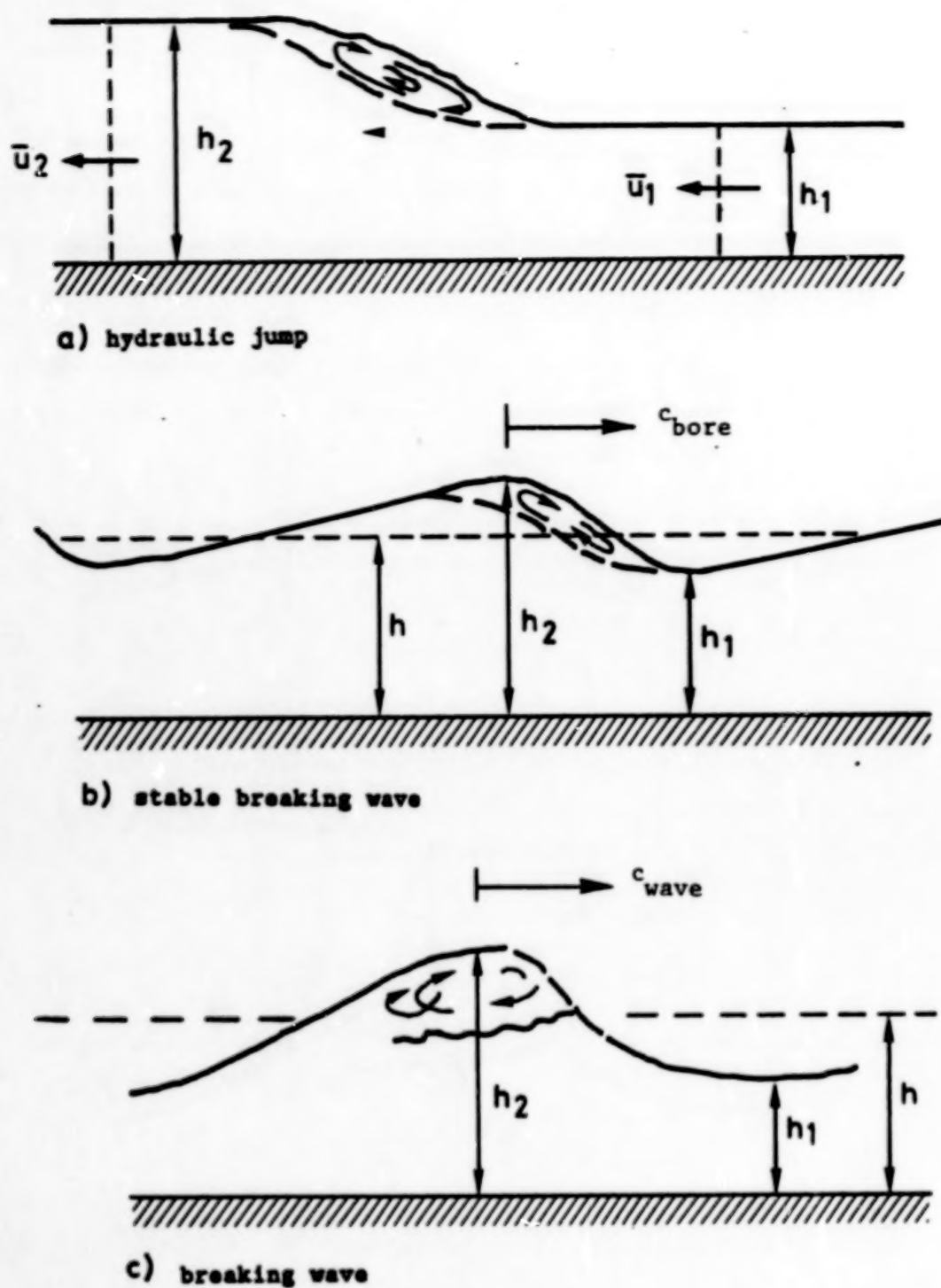


FIGURE Y.9 Definition sketches on the comparison between the hydraulic jump, the stable breaking wave and the breaking wave

Following several authors (e.g., Le Méhauté 1962, Battjes and Janssen 1978, Svendsen 1981, Stive 1982 and 1984), the dissipated energy in a single breaker in an irregular wave train can also be approximated from the similarity of the bore of a stable breaking wave to a hydraulic jump (see Figure V.9). The energy balance for the hydraulic jump leads to the following expression for the dissipated energy per unit width and time:

$$E_{hj} = \frac{\rho_w g q}{4 h_1 h_2} (h_2 - h_1)^3 \quad (V.8)$$

In which h_1 = minimum water depth before the jump

h_2 = maximum water depth beyond the jump

q = discharge per unit width

E_{hj} = energy dissipation rate per unit width

For the bore of a stable breaking wave, by using the principle of continuity ($q = h c_{bore}$), Equation (V.8) can be transformed to:

$$E_{sbw} = \frac{\rho_w g h c_{bore}}{4 h_1 h_2} (h_2 - h_1)^3 \quad (V.9)$$

In which h = mean water depth

$$c_{sbw} = \left[\frac{1}{2} g h_1 h_2 (h_1 + h_2) h^{-2} \right]^{1/4}$$

= bore propagation velocity

E_{sbw} = energy dissipation rate per unit width.

Equation (V.9) can be applied to describe the energy dissipation rate in a breaking wave by making the following assumptions:

$$c_{wave} = c_{bore} = c$$

$$(h_2 - h_1) = H_b = \text{wave height}$$

$$E_b = \alpha E_{hj} = \text{energy dissipation rate in the breaking wave per unit width.}$$

The factor α accounts for the differences between the dissipation in a breaking wave and in the hydraulic jump. α was found to be 1.3 to 1.5 for a stable breaking wave on a gentle slope. The hydraulic jump approximation underestimates the energy dissipation in this case (Stive, 1984). A similar approximation can be derived for whitecapping of wind-driven waves in open ocean conditions. In this case α ranges from 0.01 to 0.04

(Longuet-Higgins and Turner, 1974), an approximation that overestimates the energy dissipation.

$\alpha^{1/3}H$ may be interpreted as the approximate jump height. In the laboratory flumes a breaking wave is evoked because a critical value of H/h is exceeded at a certain position in the flume. This mechanism of wave breaking is similar to a stable breaking wave on a gentle slope. On the other hand, the bore is not stable but exists only temporarily (similar to whitecapping) because the wave train is irregular. It is therefore to be expected that α in the flume experiments will be somewhere between these two values. The assumption $E_b = \alpha E_{hj}$ leads to:

$$E_b = \frac{\alpha \rho_w g h c H_b^3}{4 h_1 h_2} \quad (V.10)$$

D_b in Equation (V.7) is transformed to E_b in Equation (V.10) by multiplying D_b by the time t_b , during which the bore exists. The factor α is expressed by:

$$\alpha = \frac{D_b}{t_b E_{hj}} \quad (V.11)$$

The energy dissipation per unit area D_{ba} (J/m^2) is a variable which is assumed to be important to the entrainment of surface oil by a breaking wave. The following expression can be derived:

$$D_{ba} = \frac{D_b}{l_b} = \frac{E_b t_b}{l_b} = \frac{E_b}{c} = \alpha \frac{E_{hj}}{c} \quad (V.12)$$

with l_b = bore covered length.

Besides D_{ba} , the energy dissipation per unit volume and per unit time e (J/m^3s) was assumed to be another important parameter to the break-up of submerged oil droplets. e is found by dividing D_b in Equation (V.7) by the characteristic length l_b , depth h_{bore} , and time scale t_s :

$$e = \frac{D_b}{l_b h_{bore} t_s} \quad (V.13)$$

The characteristic length scale is assumed to be the bore covered length l_b , while for the depth scale the average bore height h_{bore} is used. The characteristic time scale of the breaking wave turbulence is directly related to the time scale of the energy-containing eddies of the breaking wave turbulence. The decay of turbulent kinetic energy through energy dissipation is given by Launder and Spalding, 1972:

$$\frac{dE_k}{dt} = - C_d \frac{E_k^{3/2}}{l_s} \quad (V.14)$$

in which $E_k = \frac{D_b}{l_b h_{bore} \rho_w}$ = (average) turbulent kinetic energy density (J/kg)

l_s = length scale of the energy containing eddies,
assumed to be in the order of magnitude of 0.1 H

C_d = dimensionless constant = 0.08

The characteristic time scale t_s is of the order of magnitude of the time to halve the kinetic energy. From Equation (V.14) then follows:

$$t_s = t_{1/2E} = \frac{1.66 l_s}{C_d E_k^{1/2}} \quad (V.15)$$

V.3.2 Measurements of energy dissipation

Breaking waves in an oil slick cause the entrainment of oil into the water column, the splitting of oil into droplets and the horizontal and vertical diffusion of oil droplets. Seven different wave trains have been used in the laboratory flume, each of these wave trains evoking a single breaking wave at the oil slick. The wave trains were composed from a large number of sinusoidal wave components around a chosen average wave period T_w . A micro-computer was used to put these individual components in such a sequence that one single breaker would occur at the location of the oil slick. In the small-scale Oil Flume wave trains have been composed with the following (average) periods:

wave 1: $T_{w1} = 1.3$ s, wave 2: $T_{w2} = 1.25$ s, wave 3: $T_{w3} = 1.2$ s,
wave 4: $T_{w4} = 1.1$ s, wave 5: $T_{w5} = 1.0$ s, wave 6: $T_{w6} = 0.9$ s,
wave 7: $T_{w7} = 0.8$ s.

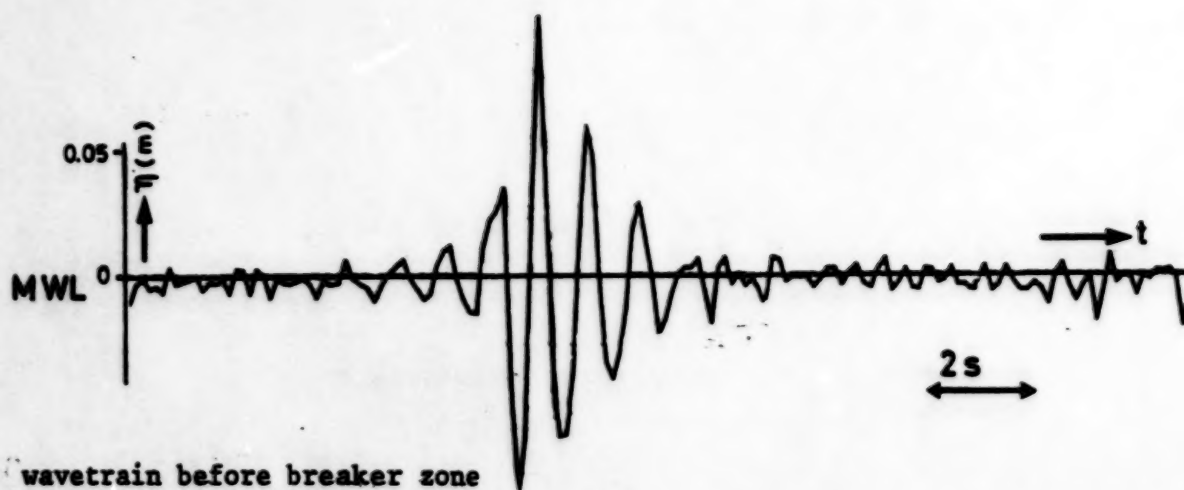


FIGURE V.10 Example of wave signal in oil flume

The wave trains have different values of dissipated energy per unit length in the breaker and different orbital movements, the latter being either strong or weak at the bottom of the flume.

Expressions were derived in Section V.3.1 to calculate the energy dissipation. Next, the methodology for measurement of the various wave parameters in the Oil Flume will be discussed.

Measurements of the wave characteristics in the Oil Flume were performed with two wave-height meters, placed before and beyond the breaker zone at an interval Δx . The water depth was $h = 0.43$ m. Because the wave-height meters did not function properly in salt water, the flume contained fresh water ($\rho_w = 1000 \text{ kg/m}^3$) during the wave experiments. In principle, a given steering signal to the wave generator might result in different wave trains whether the flume contains fresh or salt water. Measurements on wave energy were performed only in fresh water conditions, but visual observations on the breaking waves and the horizontal and vertical intrusion of dye tracer in both conditions did not show any difference. In the following sections it is assumed that the wave energy for salt water conditions is obtained from the measurements in fresh water conditions by multiplications with the factor ρ_w/ρ_{wo} (ρ_w = seawater density, ρ_{wo} = fresh water density).

Figure V.10 shows a typical example of an Oil Flume wave recording. The wave signals were integrated over a time interval Δt around the passage of the highest wave (= breaker) to obtain the integrated power spectrum of the wave train before (PS_I) and beyond (PS_{II}) the breaker zone, as described in Section V.3.1. The digital analyzer used, was capable of scanning and processing two signals at the same time. The start of the scanning of the first wave-height signal was triggered by a previously chosen minimum surface elevation, so the scanning of the second wave height meter started $\Delta x/c$ seconds after the first one. In this way, the same portion of the wave train was scanned before and beyond the breaker zone. The dissipated energy is proportional to the difference of the two values of PS. The interval of integration was chosen long enough to minimize the

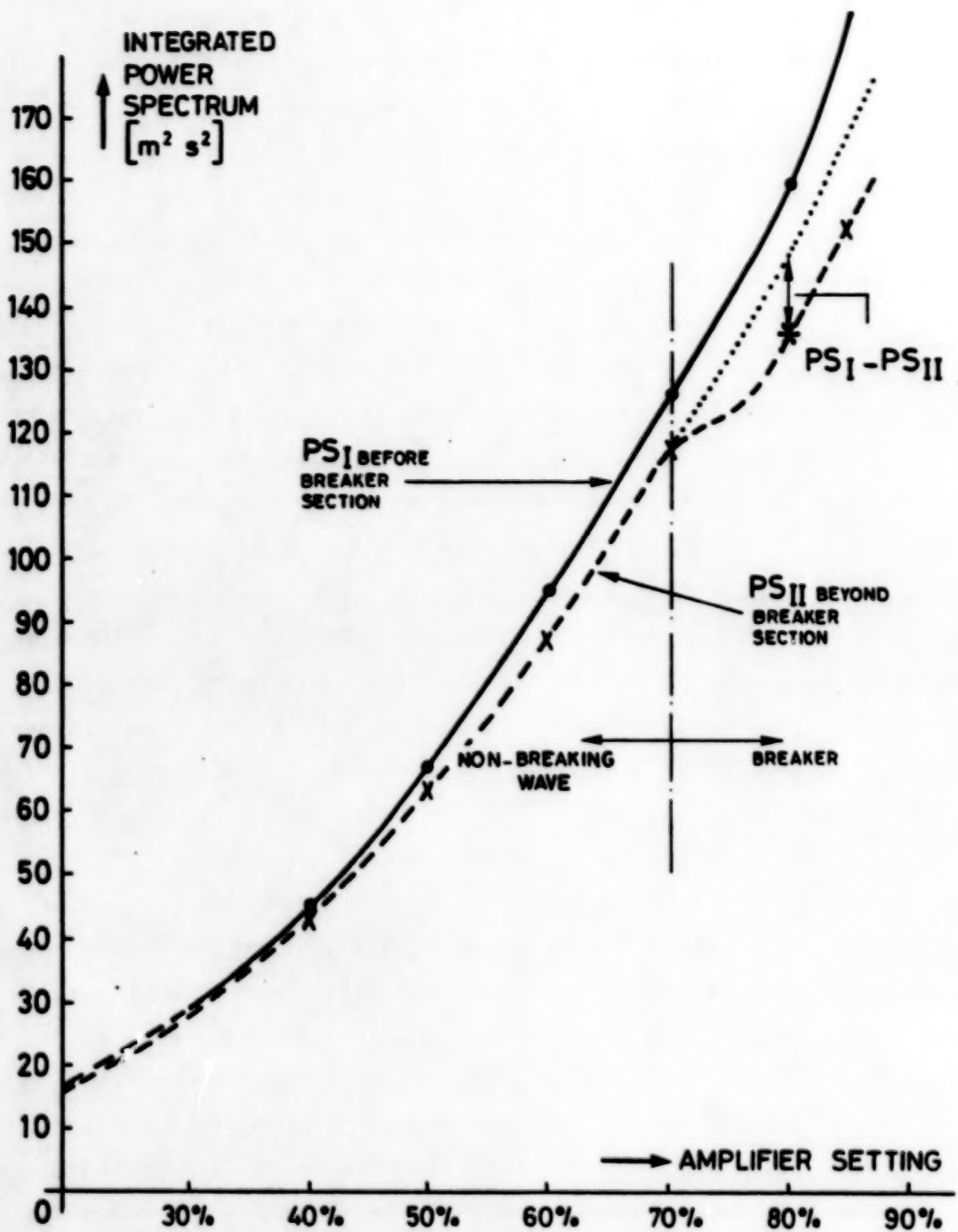


FIGURE V.11 Example of appointing the wave train energy

influence of a possible difference in the scanned parts of the wave train: $\Delta t = 16$ seconds.

The wave height and therefore also the power of the wave train could be varied by changing the steering signal (played from tape) for the wave generator. In this way it was possible to amplify the steering signal until a breaker occurred. Figure V.11 shows an example of the integrated power spectra PS_I and PS_{II} as a function of the steering signal amplification. PS_I and PS_{II} were about equal in situations without breaking waves, while PS_{II} was smaller than PS_I when a breaker occurred.

A third wave height meter was placed as close as possible to the point where the wave train would break, to measure the wave height H , as well as h_1 and h_2 . The parameters T_w and H were derived from the recordings of this meter, while f , L , and c could be calculated applying short wave theory.

The characteristic breaking wave parameters l_b , h_{bore} and t_b for each wave train were measured by taking photographs of the breaker zone at intervals of 0.1 s. The Figures V.12 to V.18 show the propagation of the seven applied wave trains, characterized by the average wave periods T_w . The successive positions of the bore at intervals of 0.1 s were plotted in one figure, from which the surface area and the water volume covered by the bore could be measured. This volume $l_b h_{bore}$ (per unit width), divided by the bore covered length l_b , leads to a value for the average bore height h_{bore} . The parameter t_b was obtained by dividing l_b by c .

The results of the wave measurements in the Oil Flume are presented in Table V.1. Obviously, the values of PS_{II} (beyond the breaker zone) were only 6% to 12% less than the values of PS_I (before the breaker zone). A relatively large error is introduced in the energy dissipation D_b , since D_b is calculated from subtraction of PS_I and PS_{II} (Equation V.7). Nevertheless the results show a decreasing absolute value of the dissipated energy from wave 1 ($T_{w1} = 1.3$ s) to wave 7 ($T_{w7} = 0.8$ s), as was to be

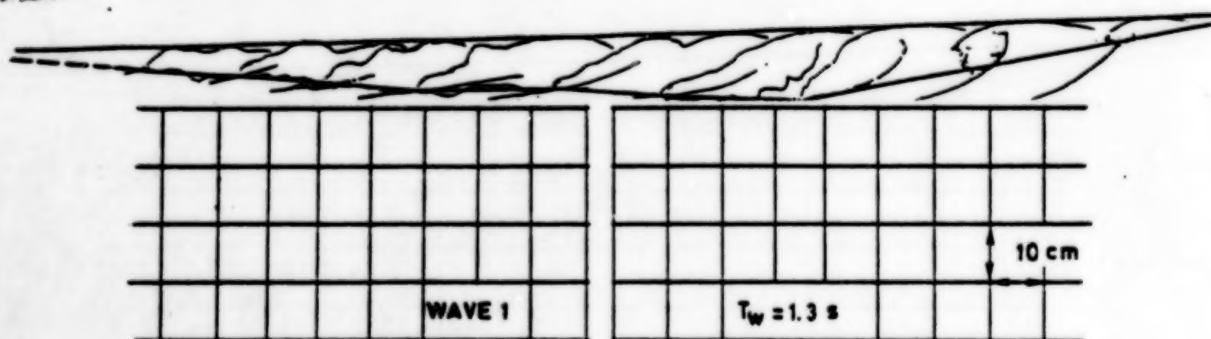
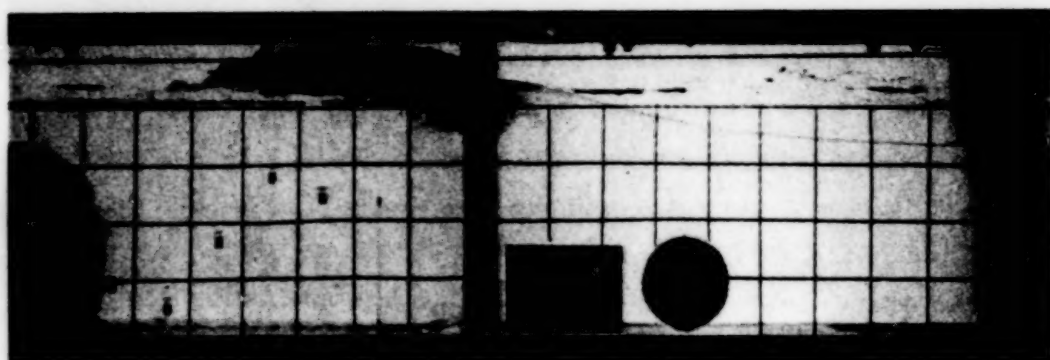
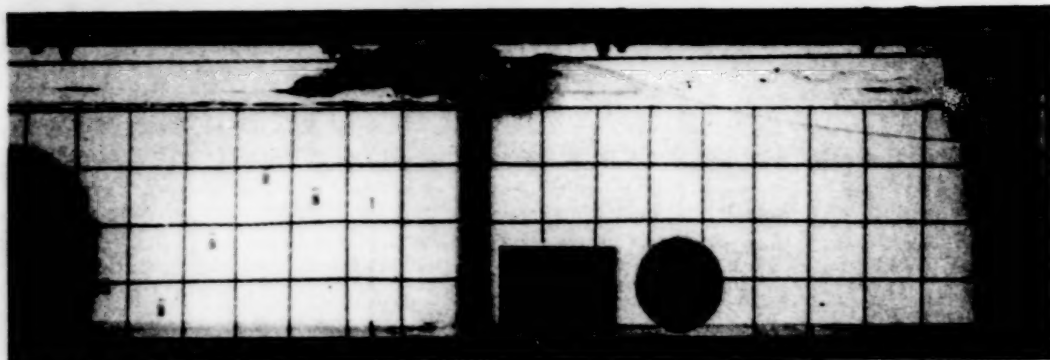
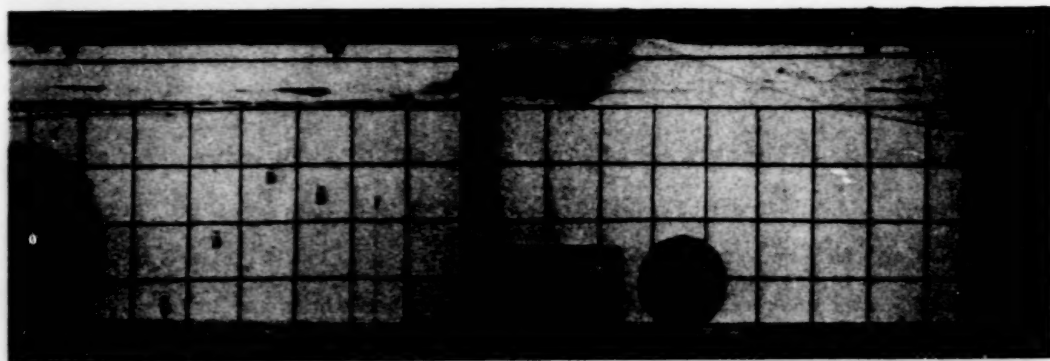


FIGURE V.12 Passage of breaking wave 1 through oil slick in oil flume

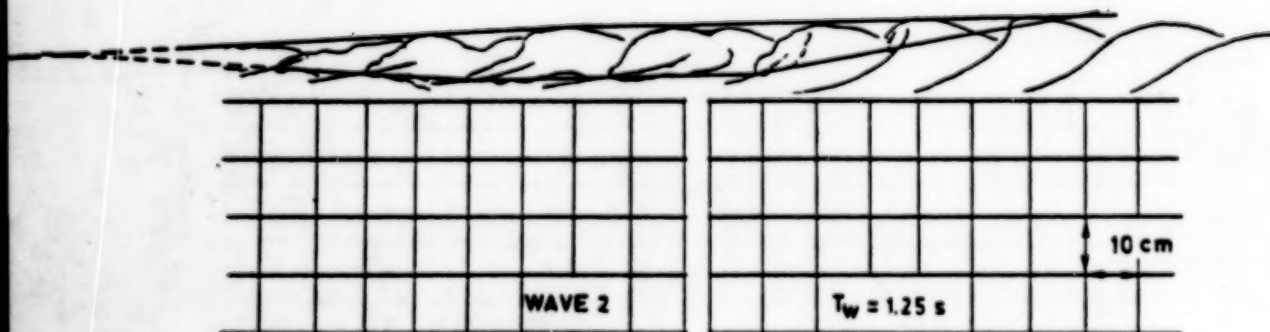
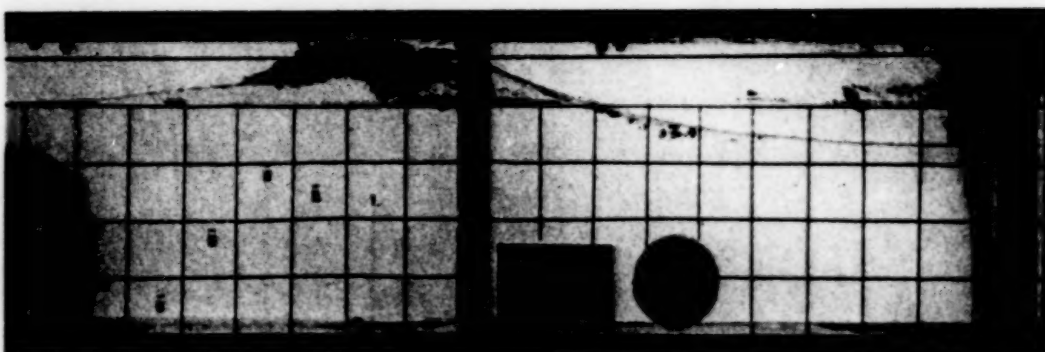
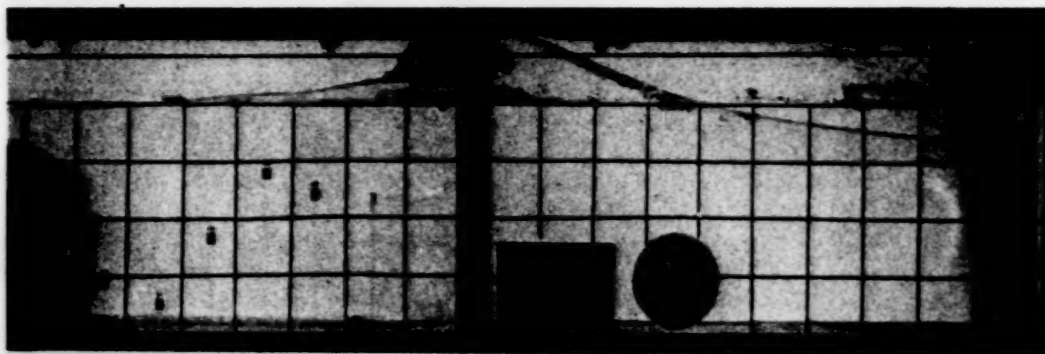


FIGURE V.13 Passage of breaking wave 2 through oil slick in oil flume

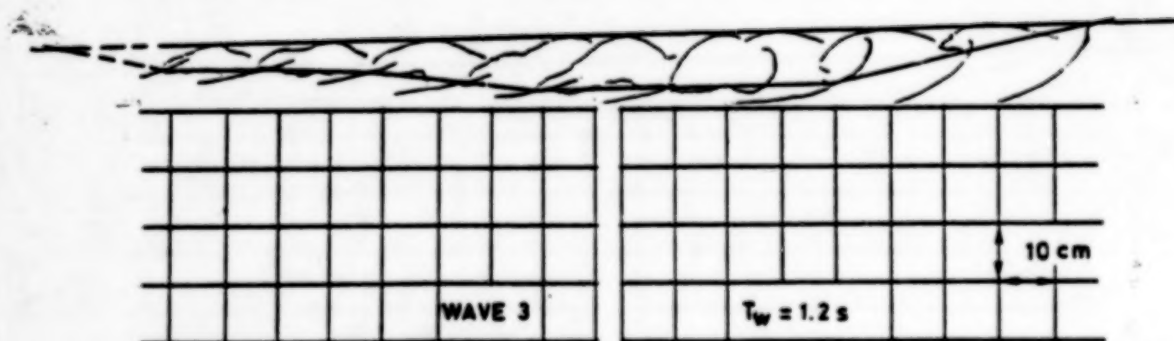
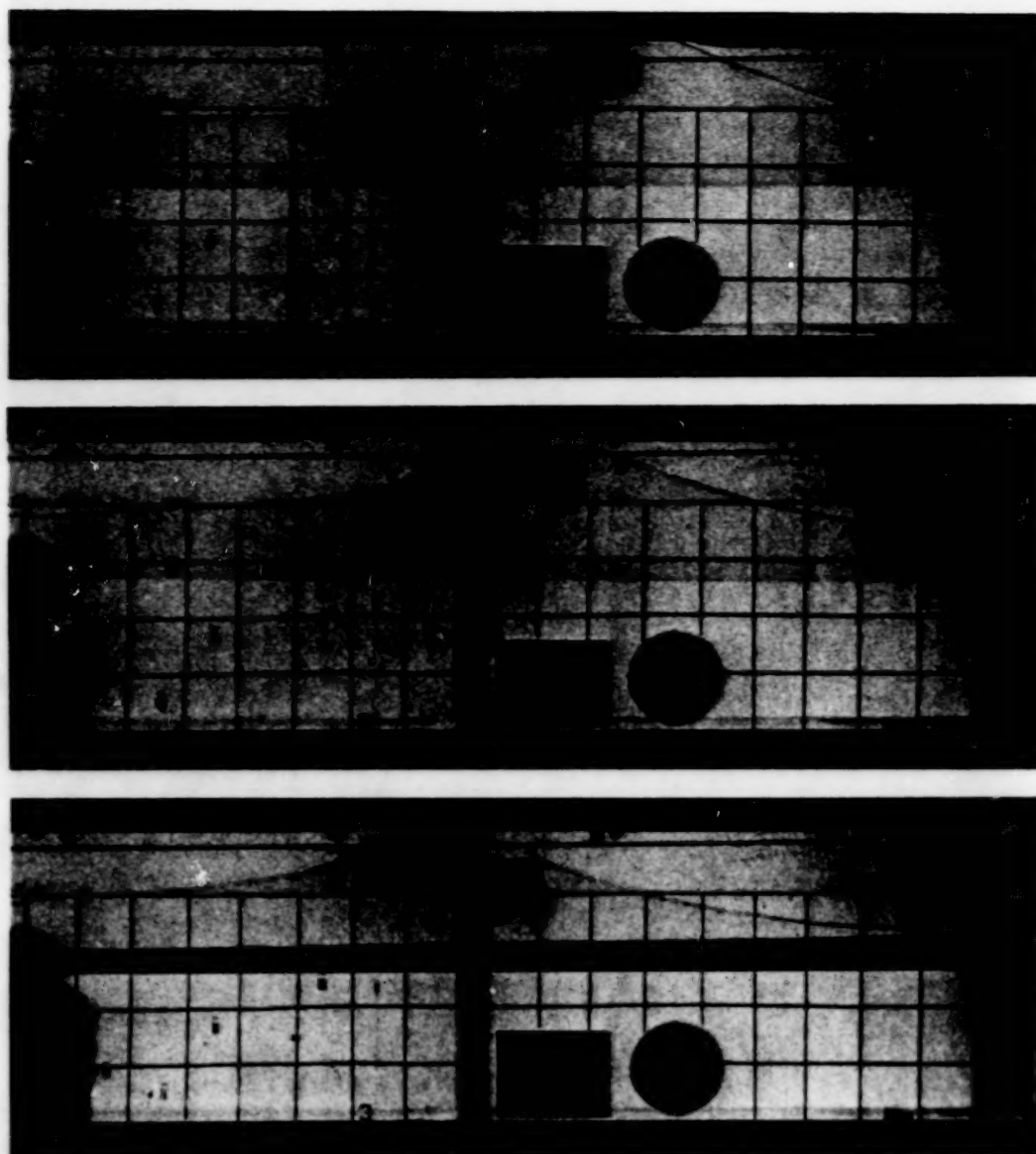


FIGURE V.14 Passage of breaking wave 3 through oil slick in oil flume

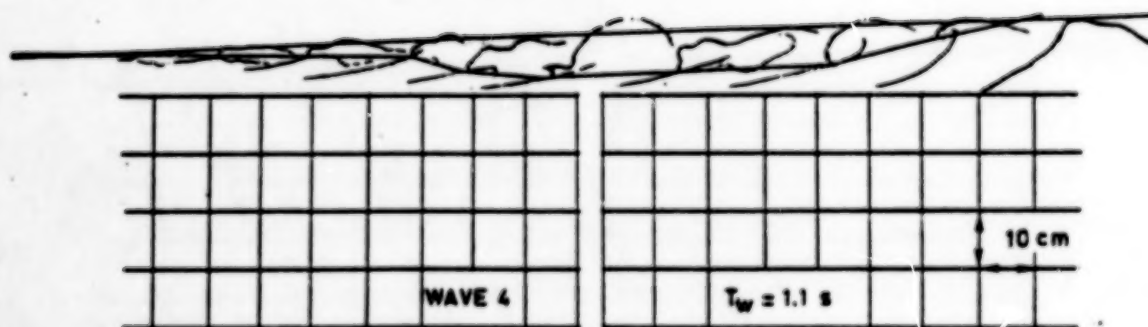
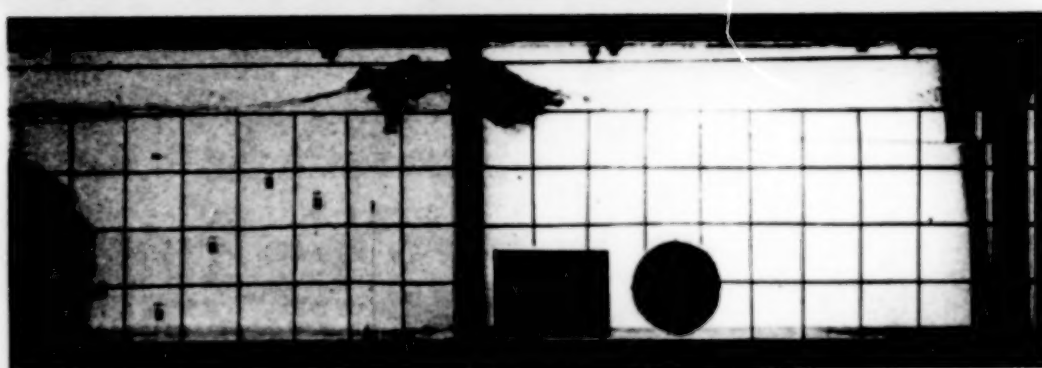
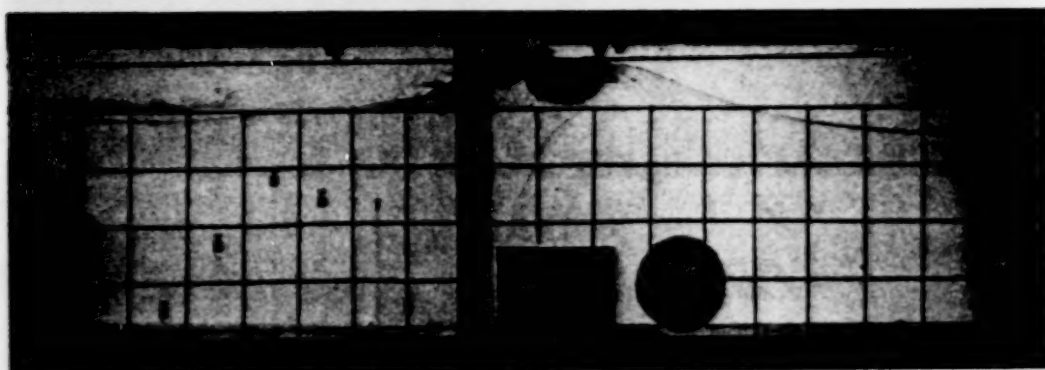


FIGURE V.15 Passage of breaking wave 4 through oil slick in oil flume

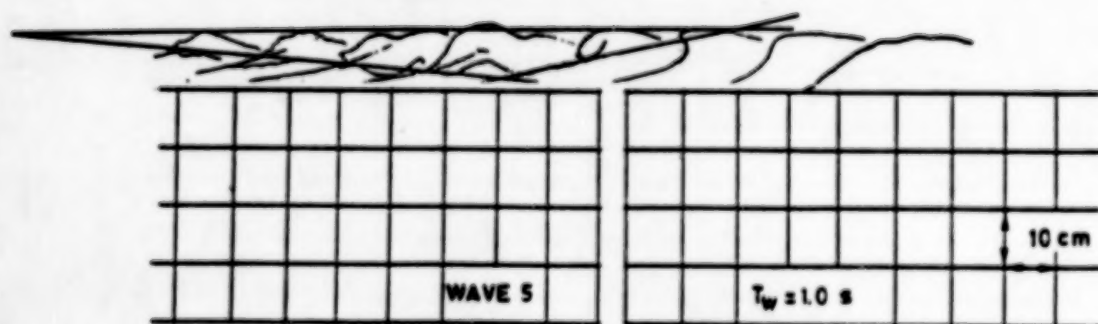
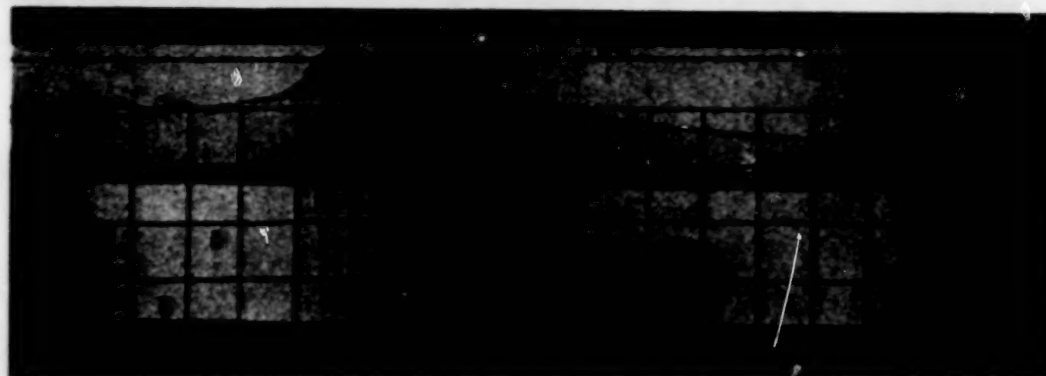
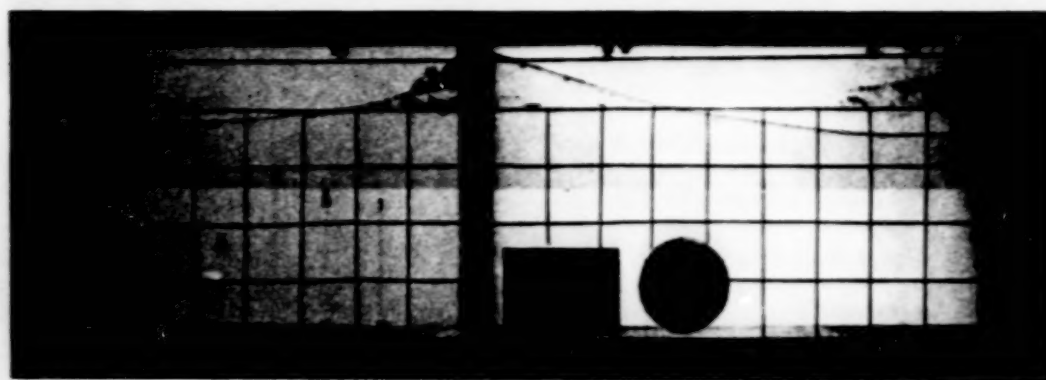


FIGURE V. 16 Passage of breaking wave 5 through oil slick in oil flume

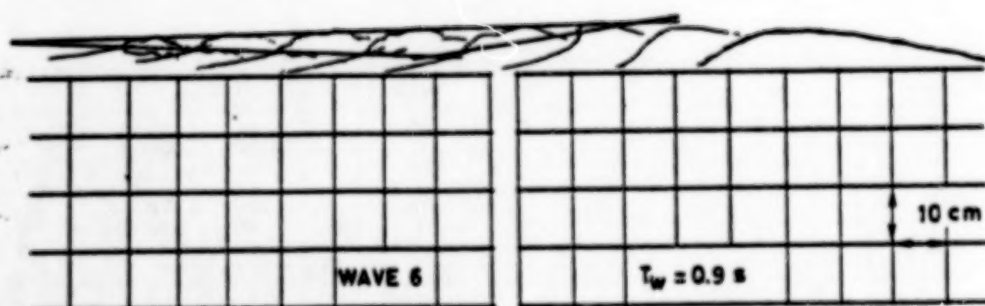
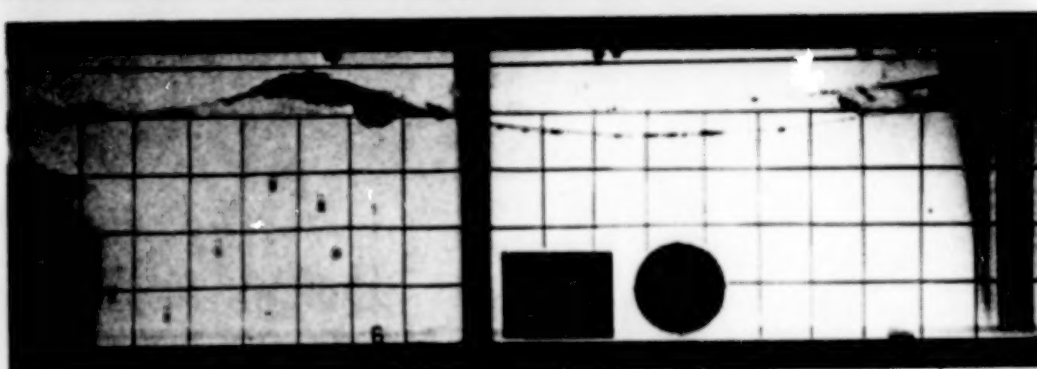
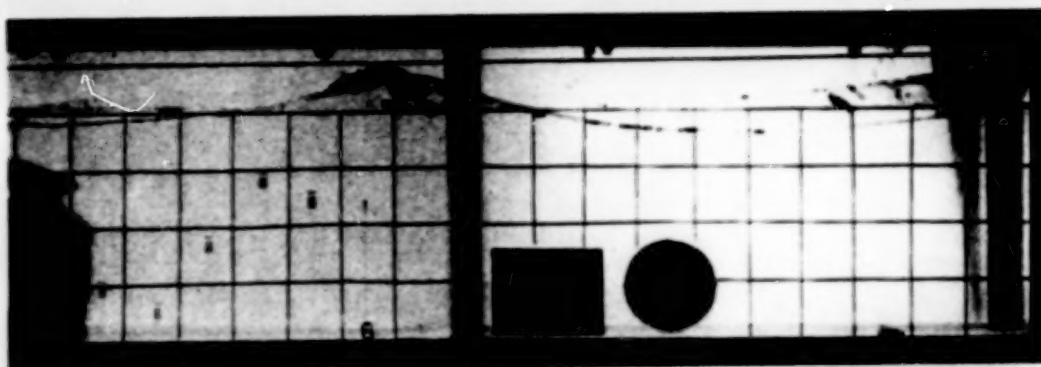
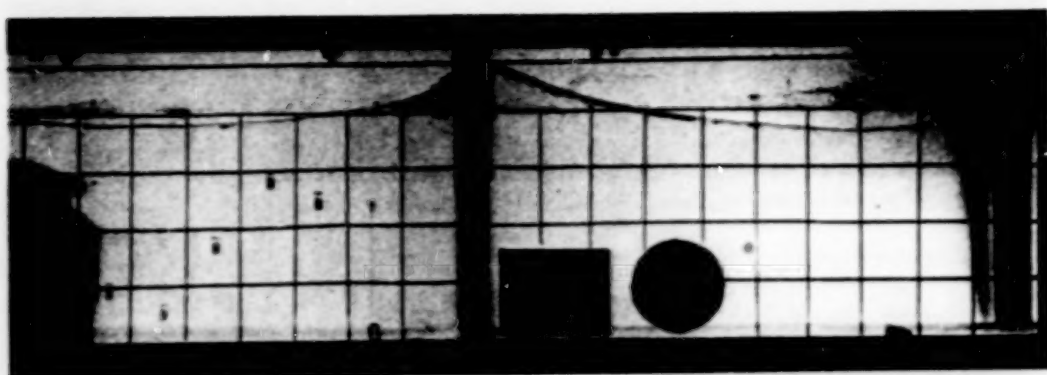


FIGURE V.17 Passage of breaking wave 6 through oil slick in oil flume

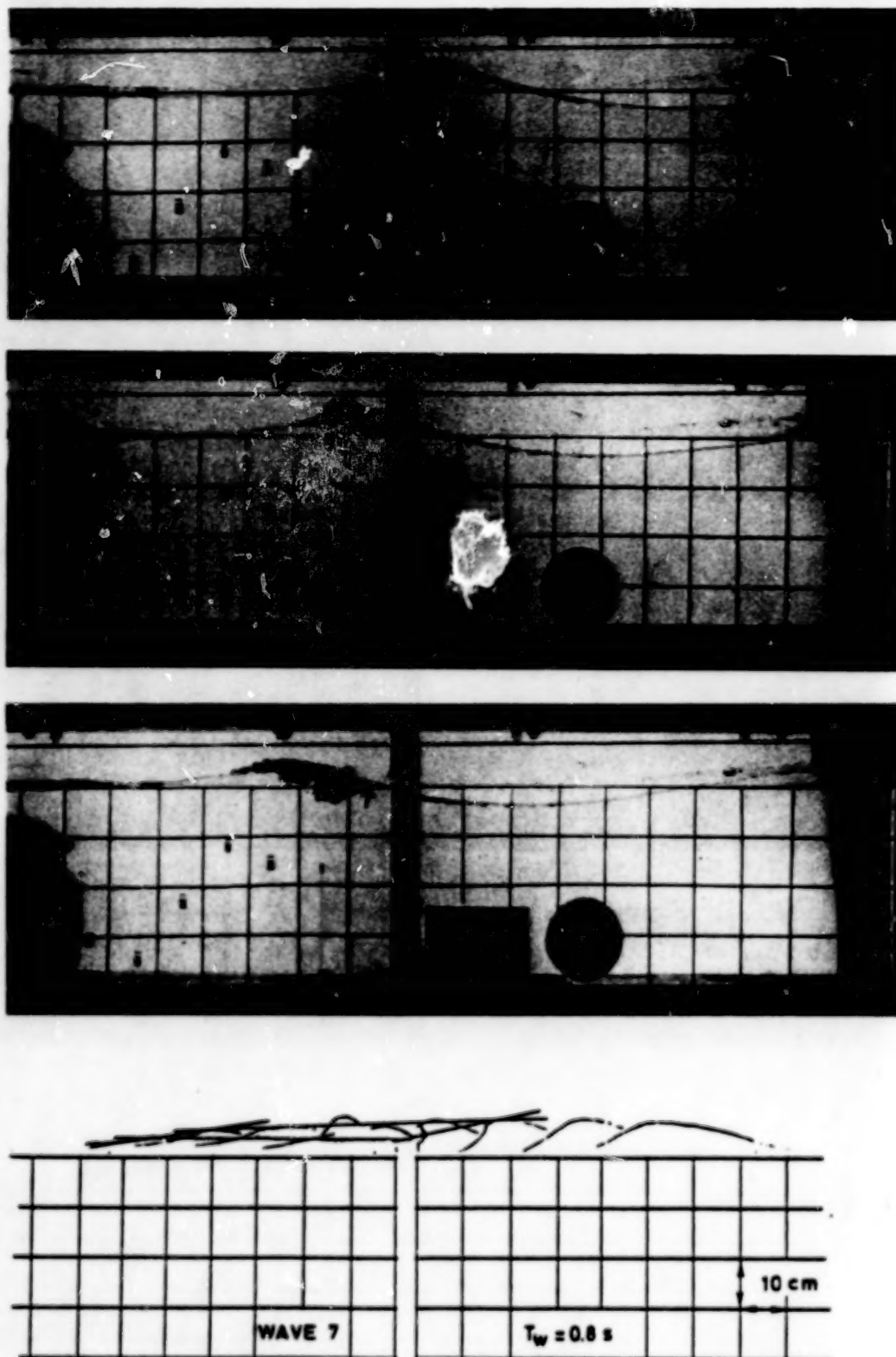


FIGURE V. 18 Passage of breaking wave 7 through oil slick in oil flume

expected. The ratio α between the measured dissipation D_b and the calculated dissipation $t_b E_{hj}$, was about 0.2 in all cases. The factor $\alpha^{1/3} H$ was roughly twice the average bore height h_{bore} . The factor was about equal to the maximum bore height, as can be seen in Figures V.12 to V.18. This indicated that the method to calculate the energy dissipation in a breaking wave from a similar hydraulic jump could be applied in these experiments by taking the maximum bore height as the approximate jump height.

Table V.1 shows that the dissipated energy per unit area D_{ba} was in the order of 10 J/m^2 for the most energetic breaking waves, and decreased from wave 1 to wave 7. The energy dissipation rate per volume, e , was of the order of $100 \text{ J/m}^3\text{s}$.

The following conclusions can be drawn from the wave experiments in the Oil Flume as regards the accuracy of the data:

- a) inaccuracies in the measurements of PS_I and PS_{II} led to a relatively large error in the energy dissipation D_b (see Equation V.7), because the integrated spectra before and beyond the breaker zone only differed by up to 15%. D_{ba} and e , in turn, were derived from D_b and the measured wave characteristics l_b and $\bar{h}_{bore}$.

The measurements clearly show a decrease of the total dissipated energy, D_b , and energy dissipation per unit area, D_{ba} , from wave 1 to wave 7. The decrease in the energy dissipation rate per unit volume, e , is less obvious (and certainly not in the Delta Flume experiments where e increased from wave 2 to wave 5, see Section VI.3 and Table VI.2). Therefore, it is more likely that e is not very dependent on the breaking wave characteristics,

- b) the hydraulic jump analog used to calculate the energy dissipation from the wave characteristics, was apparently very useful to estimate the order of magnitude. The method needs the factor α . The empirical value $\alpha = 0.15$ was found for Oil Flume conditions. (The same order of magnitude for α was found for the large-scale Delta Flume, see

Table V.1 Results of Oil Flume wave measurements

parameter	units	Wave trains with breaking waves (number and wave period $\bar{T}_w$)						
		1	2	3	4	5	6	7
		1.3 s	1.25 s	1.2 s	1.1 s	1.0 s	0.9 s	0.8 s
PS _I	$10^{-4} \text{ m}^2 \text{ s}^2$	165	136	114	74	46	24	18
PS _{II}	$10^{-4} \text{ m}^2 \text{ s}^2$	145	125	107	68	43	23	17
h	m	0.43	0.43	0.43	0.43	0.43	0.43	0.43
h ₁	m	0.37	0.37	0.35	0.36	0.37	0.39	0.39
h ₂	m	0.59	0.50	0.59	0.57	0.53	0.51	0.50
H _b	m	0.22	0.23	0.24	0.21	0.15	0.12	0.10
T _w	s	1.5	1.5	1.5	1.3	1.1	1.0	0.9
f	s ⁻¹	0.7	0.7	0.7	0.8	0.9	1.0	1.1
L	m	2.7	2.6	2.6	2.6	1.8	1.5	1.3
c	m/s	1.8	1.8	1.7	1.7	1.6	1.5	1.5
n _w	-	0.8	0.8	0.8	0.7	0.7	0.6	0.6
l _b $\bar{h}_{\text{bore}}$	m ²	0.163	0.103	0.116	0.069	0.056	0.027	0.014
l _b	m	2.47	1.83	1.87	1.64	1.34	1.17	0.72
$\bar{h}_{\text{bore}}$	m	0.07	0.06	0.06	0.04	0.04	0.02	0.02
t _b	s	1.4	1.0	1.1	1.0	0.9	0.8	0.5
D _b	J/m	28	16	9	7	3	1	1
E _k	J/kg	0.17	0.16	0.08	0.10	0.05	0.04	0.07
t _s	s	1.1	1.2	1.8	1.4	1.4	1.2	0.8
E _{hj}	J/m s	93	125	120	81	29	14	8
a	-	0.2	0.2	0.1	0.1	0.1	0.1	0.2
a ^{1/3} H	m	0.13	0.12	0.10	0.10	0.07	0.06	0.06
D _{ba}	J/m ²	11	9	5	4	2	1	1
$\frac{E_{hj}}{c}$	J/m ²	50	70	70	50	20	10	5
e	J/m ³ s	160	130	40	70	40	30	90
$\frac{E_{hj}}{ch_{\text{bore}} t_s}$	J/m ³ s	670	960	650	850	320	380	340

Section VI.3).

- c) the calculations following the hydraulic jump method also clearly show the decrease in the dissipation rate, E_{hj} , and energy dissipation per unit area, E_{hj}/c , from wave 1 to wave 7 (and from wave 2 to wave 5 in the Delta Flume, Section VI.3). The values for $\frac{E_{hj}}{c h_{bora} t_s}$ seem to support the assumption that the energy dissipation per unit volume, e , is rather independent of the wave characteristics in these experiments.

V.4 Experiments with LBPS Droplet Size Measurements

Measurements were carried out on oil droplet size distribution and oil concentration in the water column, due to wave breaking in a surface oil slick in the Oil Flume. Two series of experiments were executed with different values of the parameters as described in Section V.2. The series differ by the method of droplet size distribution measurement. Table V.2 surveys the first series of experiments executed with the laser-beam particle sizer, to be discussed in this Section. Oil-water samples were withdrawn simultaneously to determine the oil concentration by infra-red spectroscopy (see Section V.5).

The LBPS was programmed to derive oil droplet size distributions every half a minute after the time of wave breaking, t_0 . The usual droplet concentration in the measuring section required an integration time at least in the order of 30 seconds (27 seconds was applied) to obtain a real droplet distribution from the deconvolution procedure in the LBPS, other than a single contribution in the size class of maximum concentration. Twenty-four subsequent droplet distributions, each one averaged over thirty seconds, were measured. Consequently, information was gathered from $t_m = t_0 + 15$ s, with the first averaged measuring time at $t_0 + 30$ s, to $t_m = t_0 + 12$ min.

Examples of successful LBPS data with droplet size distributions at different times t_m are shown in Figure V.4. The size distributions obtained

Table V.2 Oil Flume experiments with LBPS

experiment number	oil type and weathering state	wave number $T_w(s)$	number of breaking waves	interval between breaking waves (s)	oil layer thickness h_o (mm)	temp. T (°C)
P01	PB ₀	1 1.3	1	-	0.6	17
P02	PB ₀	1 1.3	1	-	0.6	17
P03	PB ₀	2 1.25	1	-	0.6	17
P04	PB ₀	3 1.2	1	-	0.6	17
P05	PB ₀	1 1.3	1	-	1.2	17
P06	PB ₀	5 1.0	1	-	0.6	17
P07	PB ₀	7 0.8	1	-	0.6	17
P08	PB ₀	7 0.8	4	30	0.6	17
P09	PB ₃	1 1.3	1	-	0.6	17
P10	PB ₁₀	1 1.3	1	-	0.6	17
P11	PB ₀	1 1.3	4	30	0.6	17
P12	PB ₀	1 1.3	4	15	0.6	17
P13	PB ₀	1 1.3	4	60	0.6	17
P14	PB ₀	1 1.3	10	30	0.6	17
P15	PB ₀	5 1.0	4	30	0.6	17
P16	Eko	5 1.0	1	-	0.6	17
P17	Eko	7 0.8	1	-	0.6	17
P18	Eko	1 1.3	1	-	0.6	17
P19	Eko	4 1.1	1	-	0.6	17
P20	Eko	6 0.9	1	-	0.6	17
P21	Eko	3 1.2	1	-	0.6	17
P22	Eko	2 1.25	1	-	0.6	17
P23	PB ₀	1 1.3	1	-	0.6	9
P24	PB ₀	1 1.3	4	30	0.6	9
P25	PB ₀	2 1.25	1	-	0.6	9

ranged from $d_0 = 20 \mu\text{m}$ to $d_0 = 400 \mu\text{m}$. However, the quality of the most measured distributions in the various experiments was poor as compared with the examples in Figure V.4, with few and sometimes irregular size class contributions to the total distribution. Moreover, the mutual results of the measurements at the four different depths were not always consistent. The poor quality of the LBPS measurements was probably due to the following features:

- a) the concentration of the dispersed oil droplets is low relative to the measuring capability of the LBPS.
- b) the dispersed oil droplets were rather irregularly distributed over the length of the flume, while the two particle sizers were placed at fixed positions along the flume. (Figure V.19 shows an example of irregular distribution of oil droplets immediately after the breaking wave passage. See also Figure V.6).
- c) the measurements at four depths were obtained from two different experiments because only two particle sizes were available.

The poor LBPS measurements due to the mentioned features, and the fact that it was not possible for the LBPS to measure small droplets in a droplet size distribution with a considerable "background" of large droplets (discussed in Appendix A.2.1) were the reasons to develop a different technique for droplet size distribution measurements in the present experimental circumstances. The experiments with the new measurement techniques are described in Section V.5.

The LBPS data obtained in the experiments surveyed in Table V.2, were reduced by derivation of the average droplet size, d_{50} , from the measured droplet size distribution. Figure V.20 shows a successful example of d_{50} versus time t_m at four depths z below the water surface. The decreasing value of d_{50} with increasing depths z , and the decreasing d_{50} in the course of time t_m was, at least for the greater part, due to continuing resurfacing of large oil droplets. Whether different d_{50} values at different depths was also due to different intrusion depths from the wave breaking process cannot be derived from these data.

Generally, a considerable spread in d_{50} was found, both in time t_m and in

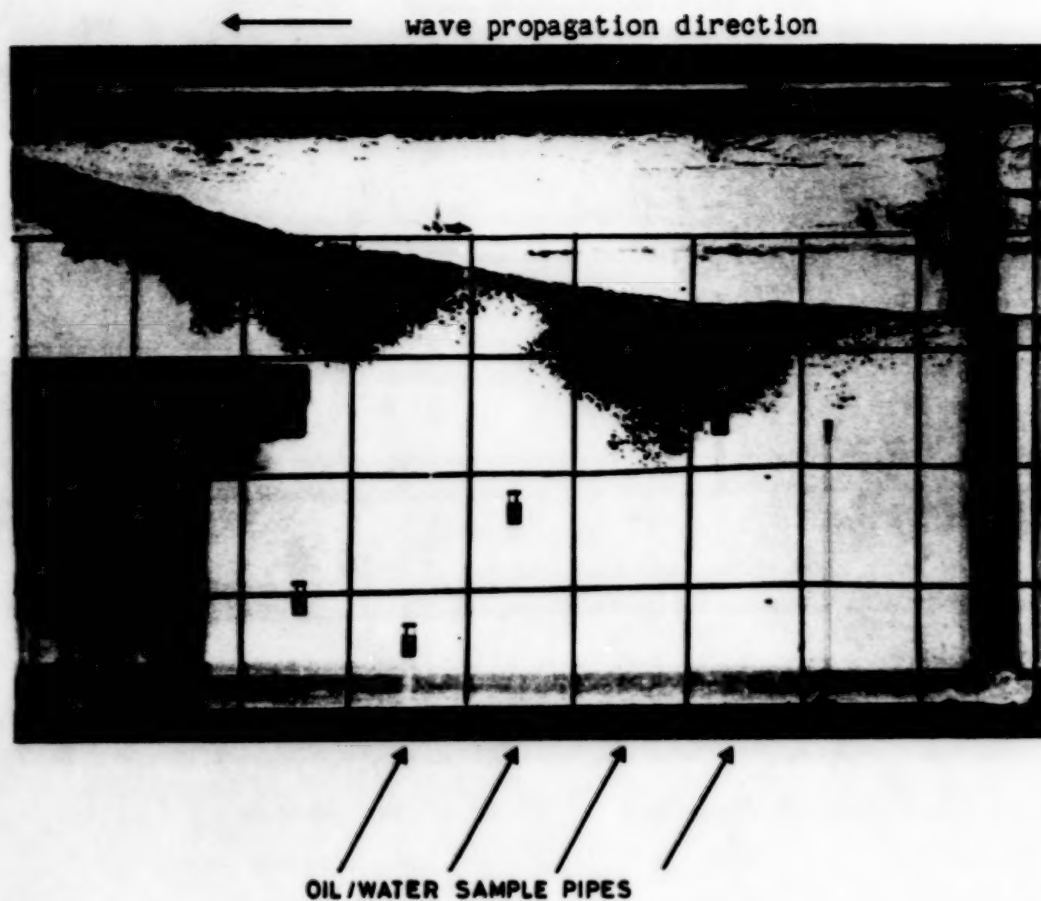


FIGURE V. 19 Oil dispersion immediately after passage of the breaking wave

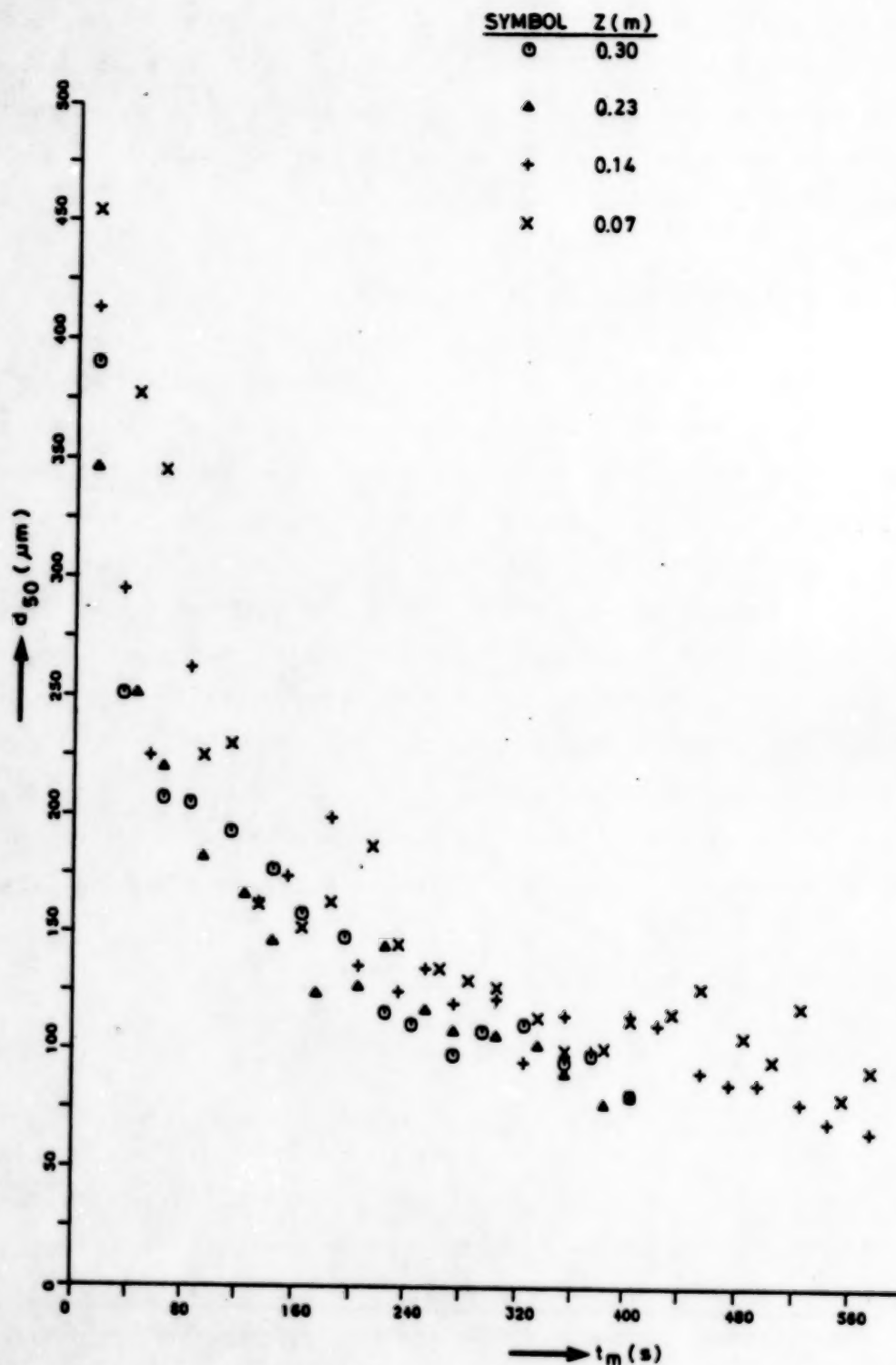


FIGURE Y.20 Droplet size d_{50} versus t_m at various depths z below the water surface

depth z within an experiment. Therefore, the derived d_{50} values were averaged over the four depths to a single value per time t_m . The Figures V.21 to V.23 show results of d_{50} as a function of the different wave (indicated by the wave period T_w) at $t_m = 15$ s, 60 s and 240 s respectively. Conclusions from the droplet size distribution measurements in this series of experiments are drawn in combination with the results of the second series of experiments described in Section V.5.

V.5 Dispersed Oil Concentration Measurements

Simultaneous with the LBPS measurements, oil-water samples of 0.6 litre were taken at 1 minute and 4 minutes after wave breaking. The samples were withdrawn at various depths, through 4 small pipes on the bottom of the flume. (See Figure V.19). The oil concentrations were determined by infra-red spectroscopy. Similar to the d_{50} measurements in Section V.4, a considerable irregularity was found for the values of C_o at different depth and at different times, probably due to the features described in Section V.4 a and b. Therefore, the oil concentrations for various depths were averaged to a single value per time. Figures V.24 and V.25 show the results for the various experiments as a function of wave period T_w . The oil concentration data were used for the derivation of equations describing the oil entrainment in different circumstances, see Section VII.

V.6 Experiments with Microscopic Droplet Size Measurements

V.6.1 Introduction

Section V.4 described the experiments on oil droplet size distributions at various depths measured by two Laser Beam Particle Sizers. The applied optical systems should enable determination of droplet sizes in the 20-1900 μm range, divided into 20 subranges. The oil concentrations in water samples from various depths were determined by infra-red spectroscopy. However, the measured droplet size distribution did not meet the requirements due to the following reasons:

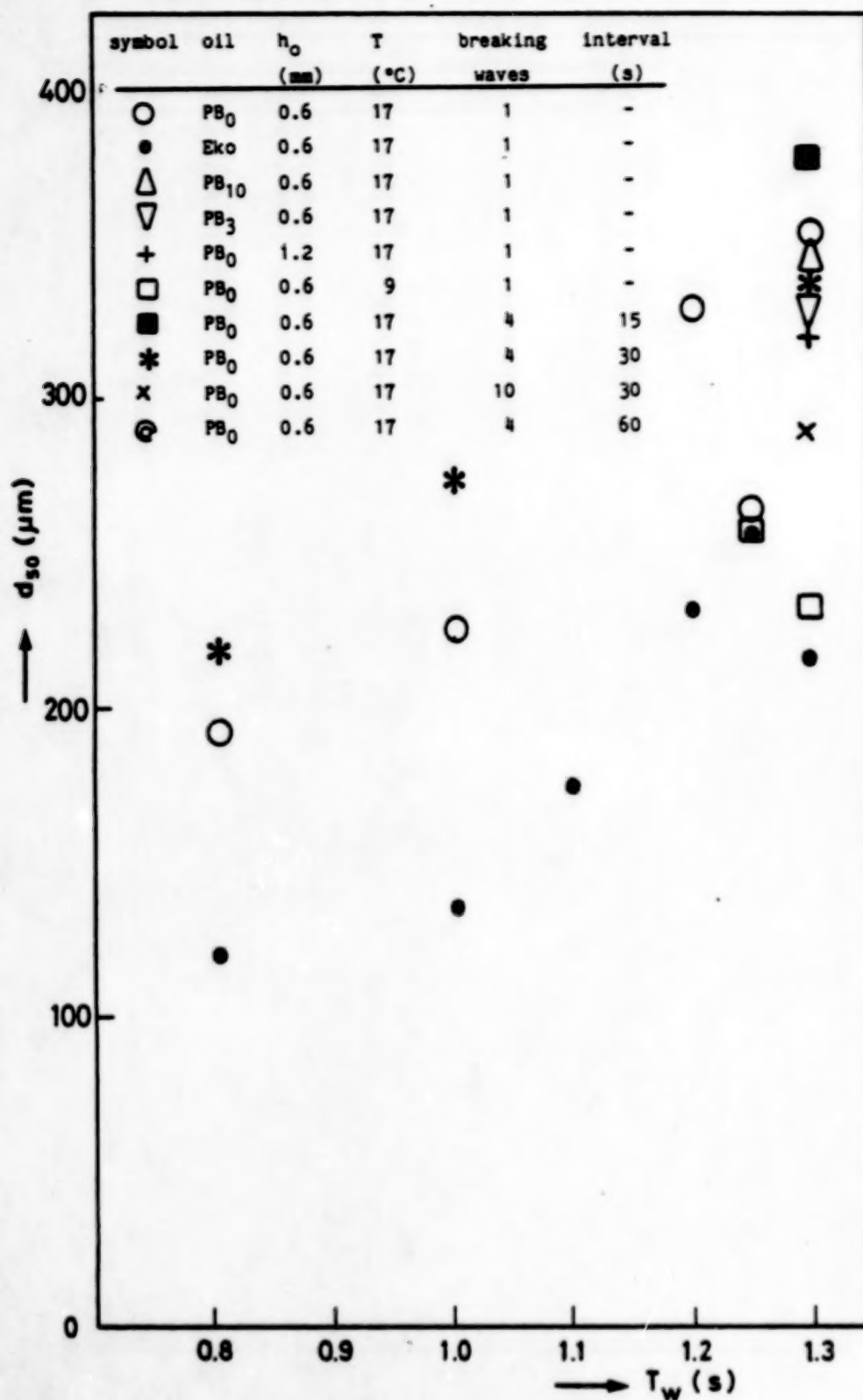


FIGURE V. 21 d_{50} at $t_m = 15$ s for different experiments

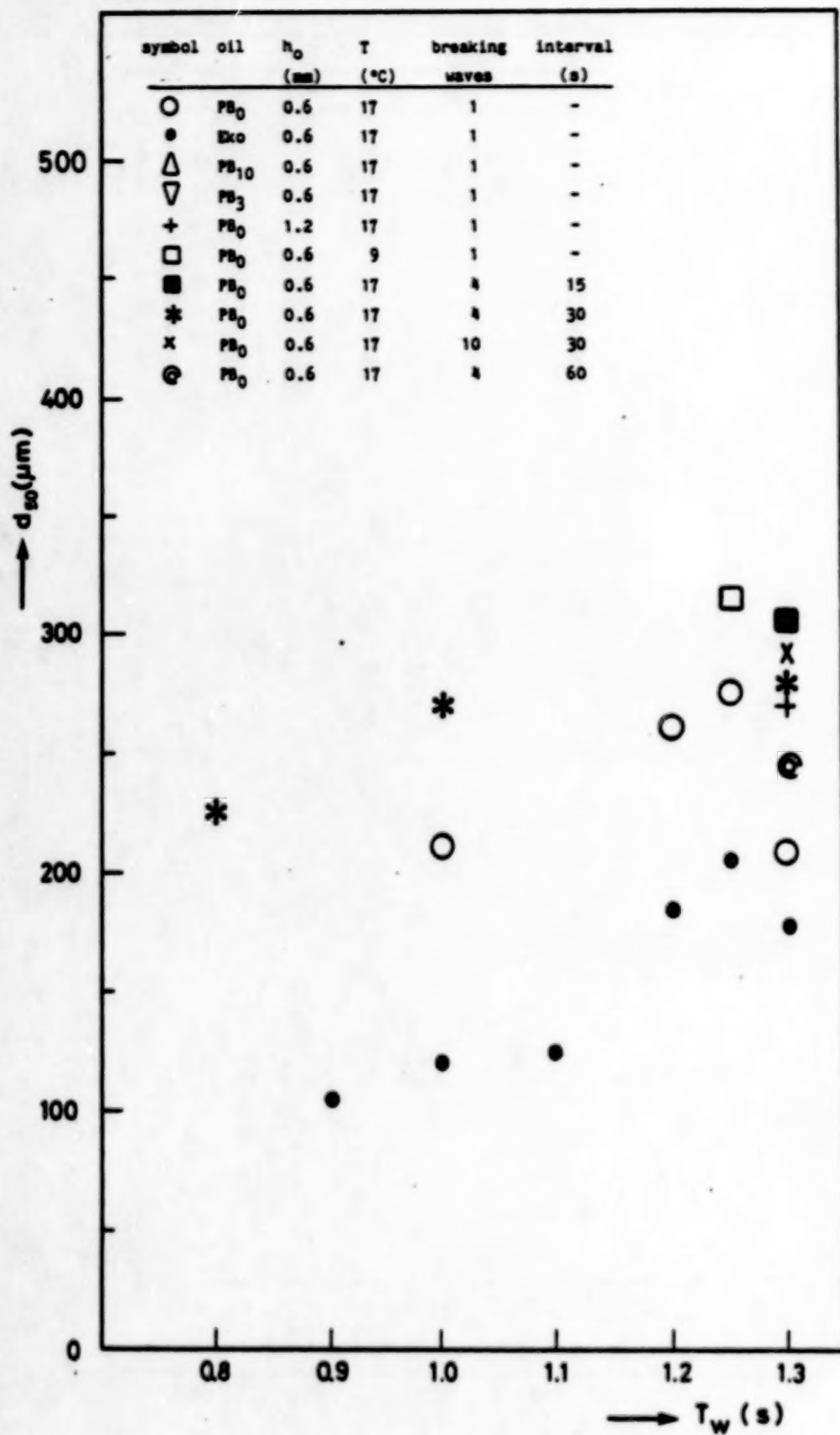


FIGURE V.22 d_{50} at $t_m = 60$ s for different experiments

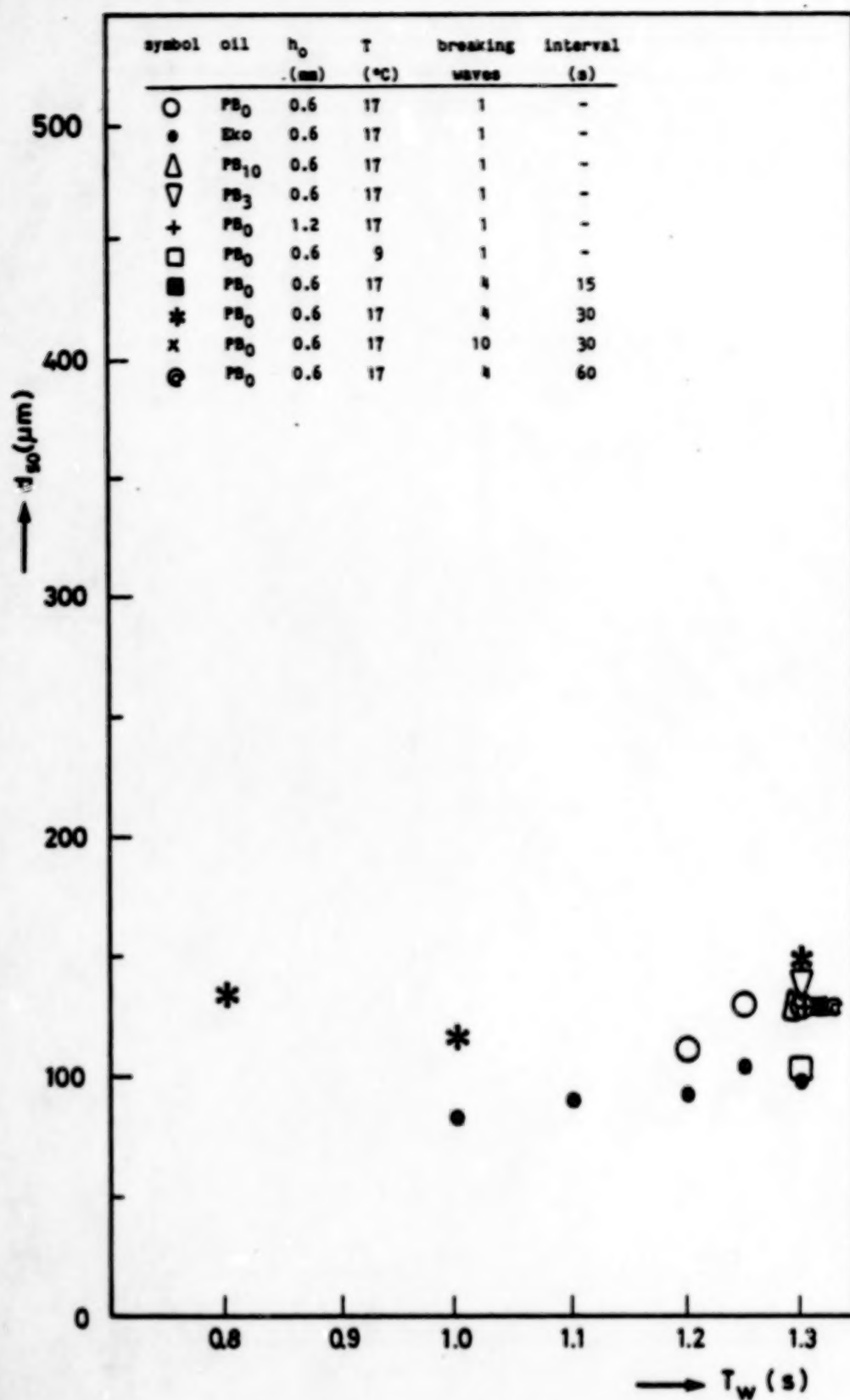


FIGURE V. 23 d_{50} at $t_m = 240$ s for different experiments

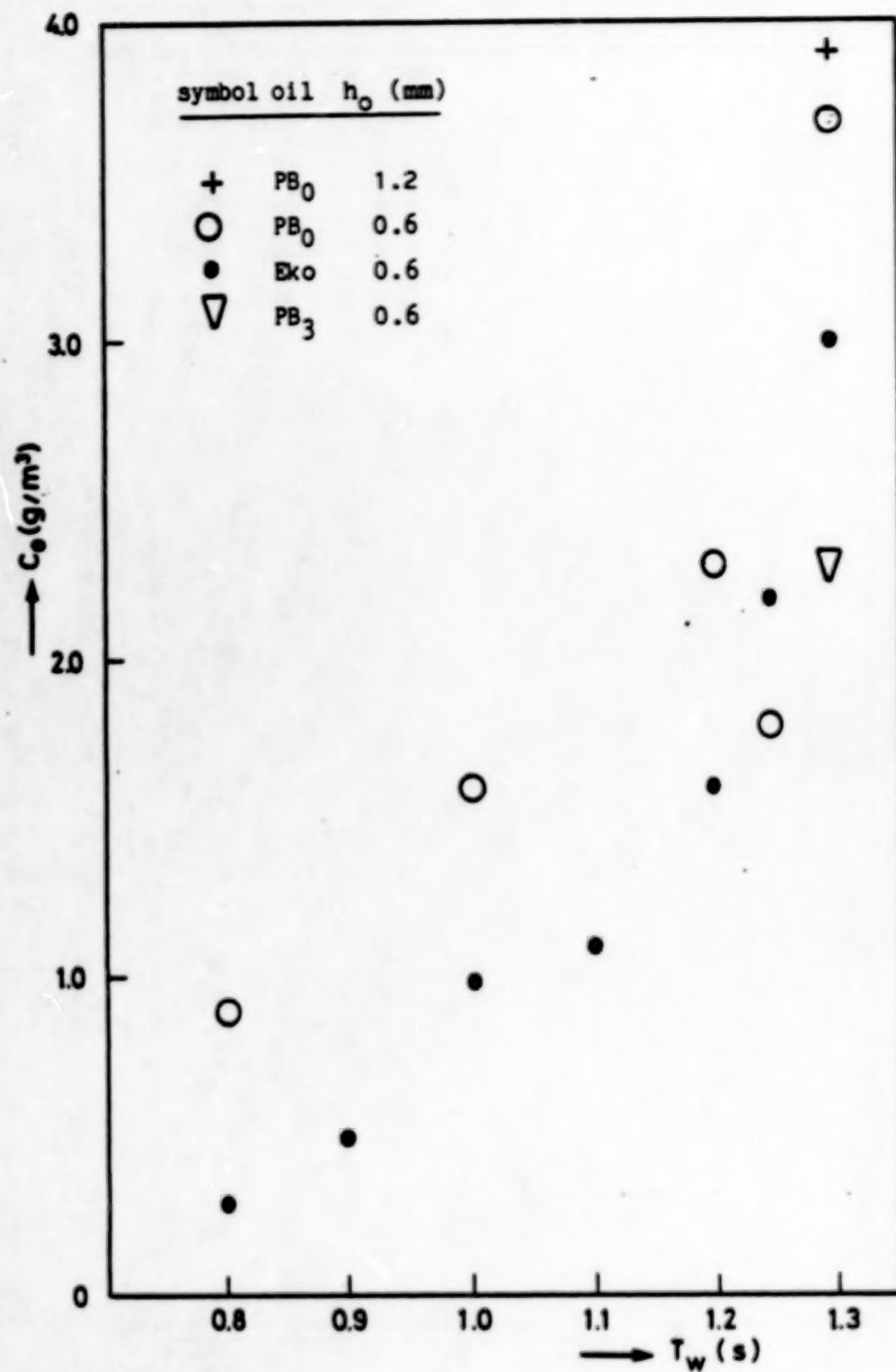


FIGURE V. 24 Depth-averaged oil concentration at $t_m = 40$ s for different experiments

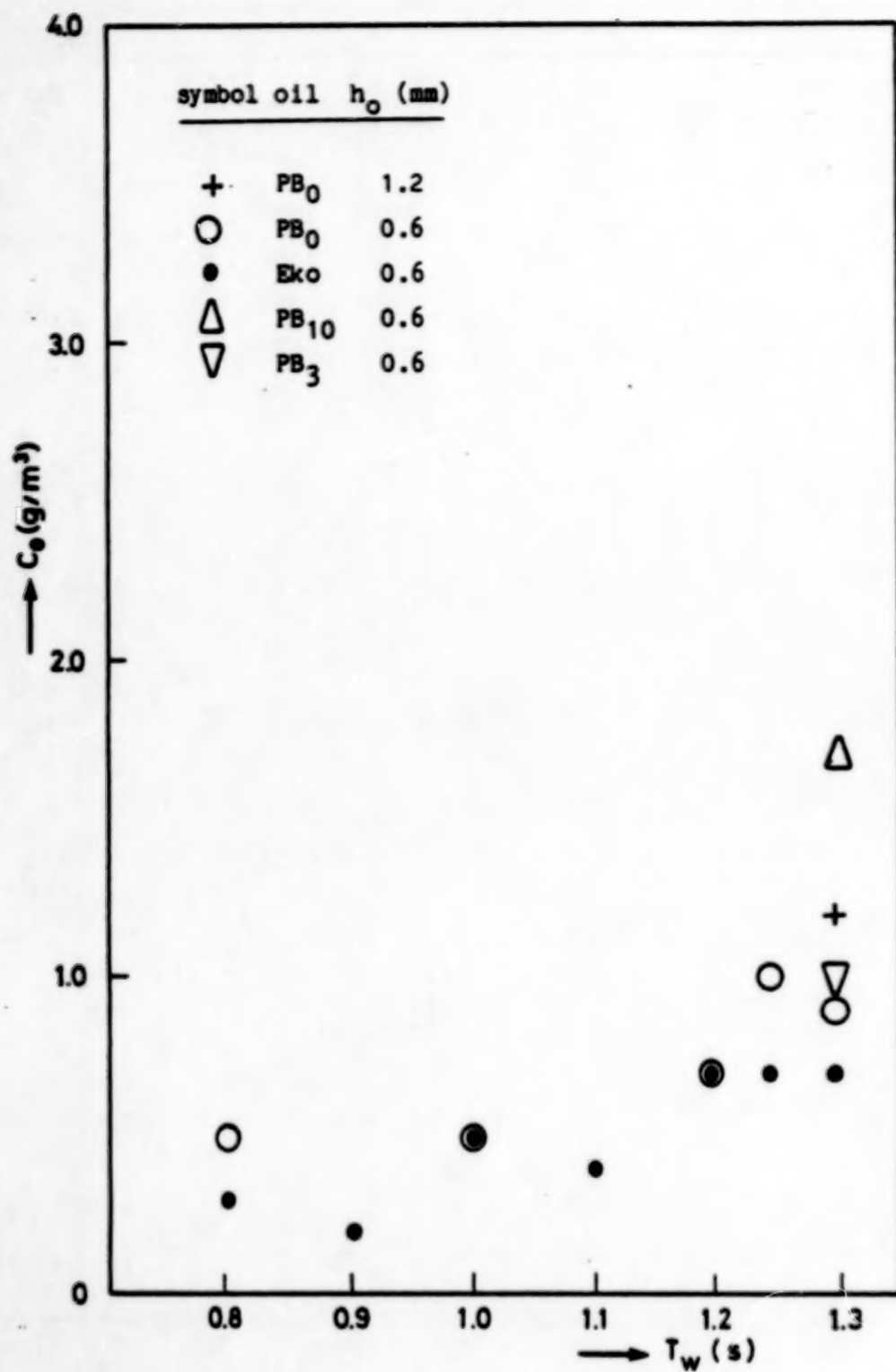


FIGURE V.25 Depth-averaged oil concentration at $t_m = 240$ s for different experiments

Tabel V.3 Oil Flume experiments with samplers

experiment number	oil type, weathering state	wave			oil layer thickness h_o (mm)	tempe- rature T (°C)	Figures
		number	T_w (s)	H_b (m)			
S2	PB ₀	2	1.25	0.20	0.6	15	V.31 to V.33
S21	PB ₀	2	1.25	0.20	0.6	15	V.82 to V.84
S3	PB ₁₀	2	1.25	0.20	0.6	15	V.34 to V.36
S4	Ekofisk	2	1.25	0.20	0.6	15	V.37 to V.39
S17	PB ₀	2	1.25	0.20	0.6	2	V.70 to V.72
S18	Ekofisk	2	1.25	0.20	0.6	2	V.73 to V.75
S19	PB ₀	2	1.25	0.20	0.6	8	V.76 to V.78
S20	Ekofisk	2	1.25	0.20	0.6	8	V.79 to V.81
S9	PB ₀	3	1.2	0.20	0.2	15	V.46 to V.48
S8	PB ₀	3	1.2	0.20	0.6	15	V.43 to V.45
S10	PB ₀	3	1.2	0.20	1.2	15	V.49 to V.51
S7	PB ₁₀	3	1.2	0.20	0.6	15	V.40 to V.42
S11	Ekofisk	3	1.2	0.20	0.6	15	V.52 to V.54
S14	PB ₀	5	1.0	0.15	0.6	15	V.61 to V.63
S15	PB ₁₀	5	1.0	0.15	0.6	15	V.64 to V.66
S16	Ekofisk	5	1.0	0.15	0.6	15	V.67 to V.69
S13	PB ₀	7	0.8	0.10	0.6	15	V.58 to V.60
S12	Ekofisk	7	0.8	0.10	0.6	15	V.55 to V.57

- a) the accuracy of the measured distributions was low due to the low concentration of oil in the water.
- b) droplets in a certain subrange could only be detected if the oil volume in the subrange exceeds the value of 0.1 percent of the oil volume in the entire range of measurement.
- c) a considerable number of oil droplets will probably exist in the range below 20 μm , beyond the range of the LBPS.

The restricted usefulness of the LBPS has led to the development of a sampling device (see the description in Appendix A.2.3) which enabled the reliable determination of oil droplets with sizes down to 50 μm by macrophotography and sizes down to 3 μm by visual microscopy. This sampler enabled the determination of the relative droplet size distribution and the absolute oil concentration.

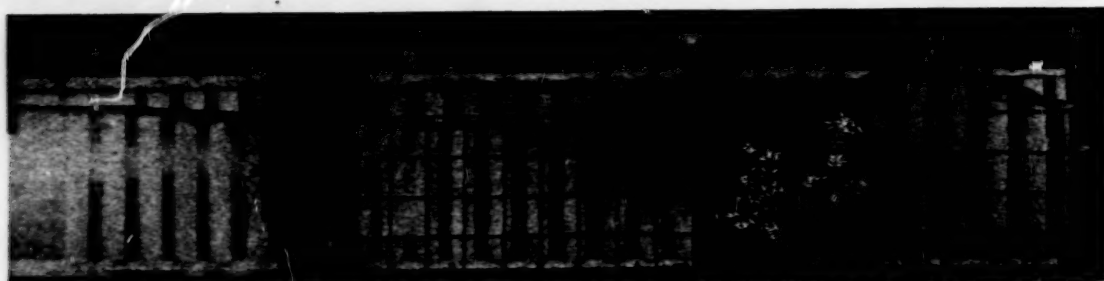
A series of experiments with the samplers were performed in the Oil Flume. The various experiments are listed in Table V.3. The experiments were more or less a repetition of some experiments with the LBPS, discussed in Section V.4.

V.6.2 Experimental set-up

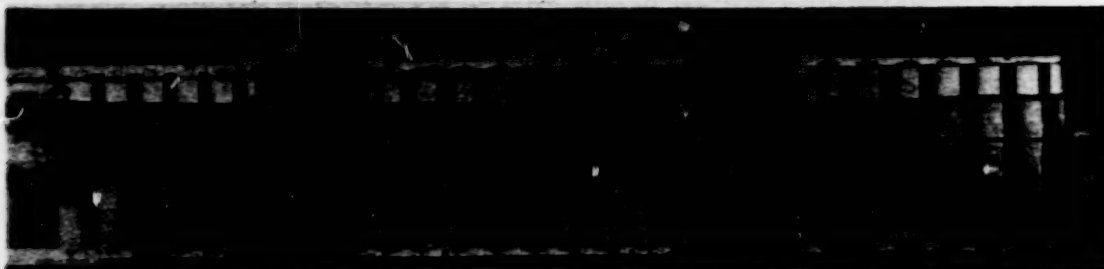
The following steps were taken during each experiment.

The selected wave train with a single breaking wave was observed in a dye experiment to obtain the extension of the turbulence field in course of time. The dye tracer was sprayed on the water surface in the flume before the passage of the breaking wave. Figure V.26 shows the breaking wave passage, at $t_m = 0$. The subfigures b, c, d, e show the increasing dye cloud at $t_m = 5 \text{ s}$, 20 s, 65 s and 125 s respectively.

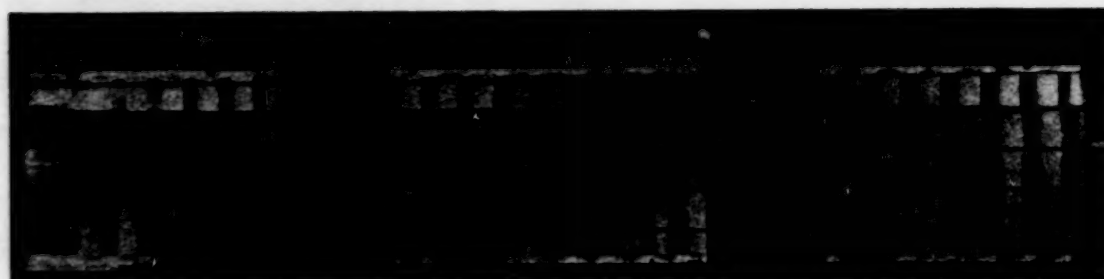
Ten oil-water samples were withdrawn during an oil dispersion experiment. The ten samplers were mounted at various depth on bars which in turn were mounted on a cart moving longitudinally over the flume (see Figures V.29 and V.30). A sample was identified by the depth z , the period during which



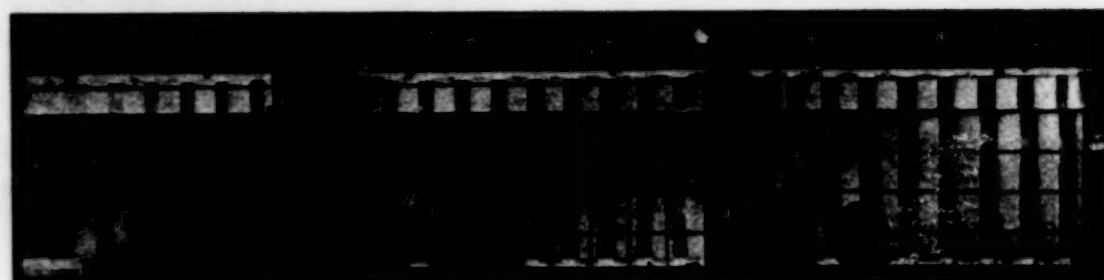
a) $t_m = 0$



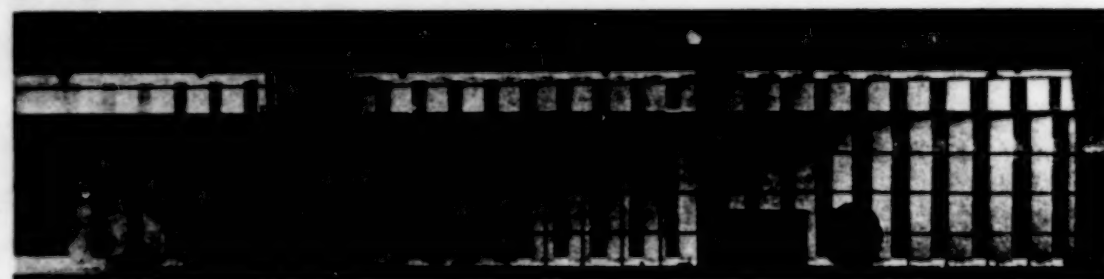
b) $t_m = 15 \text{ s}$



c) $t_m = 30 \text{ s}$

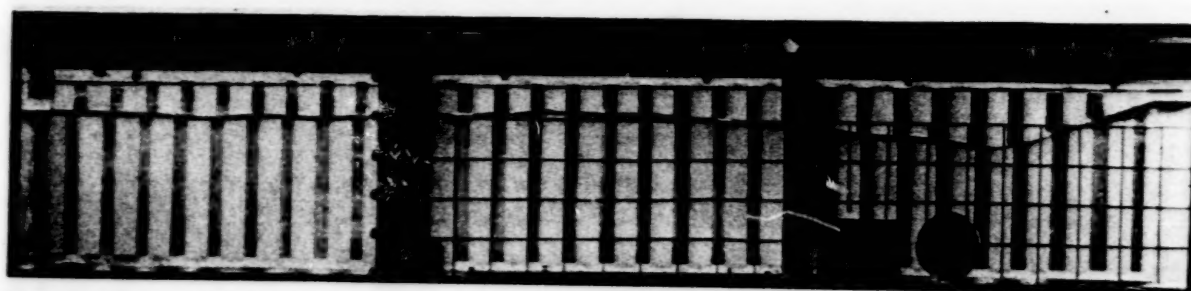


d) $t_m = 60 \text{ s}$

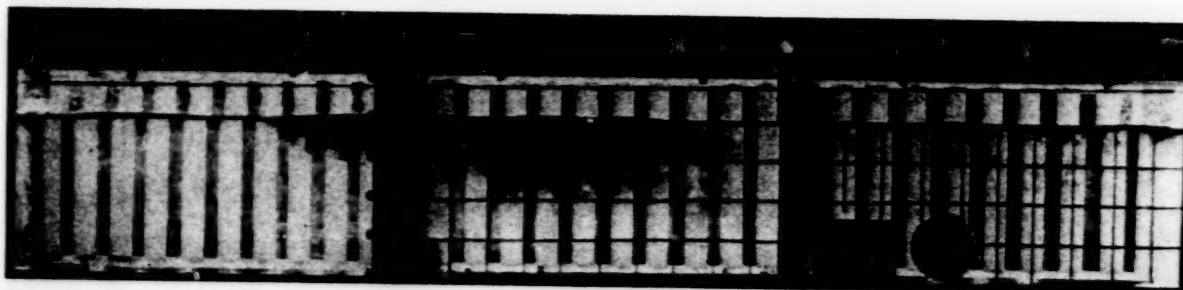


e) $t_m = 120 \text{ s}$

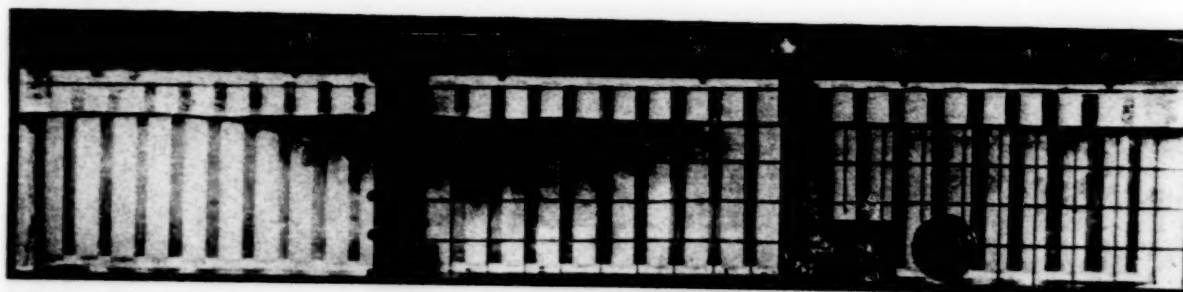
FIGURE V. 26 Dye experiment on breaking-wave turbulence field. wave 2



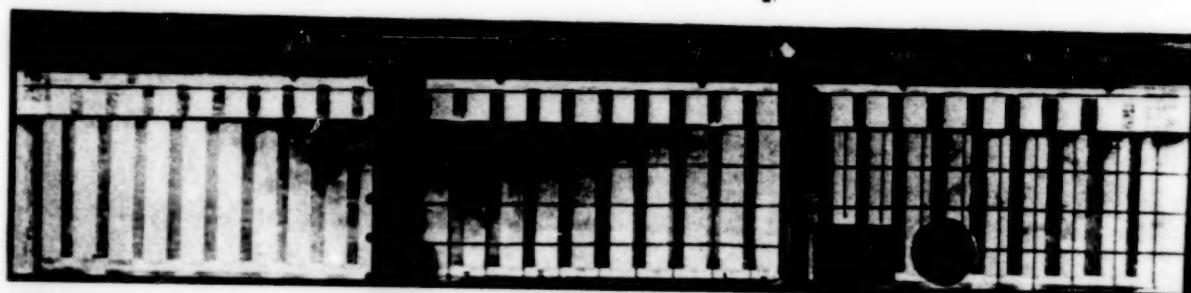
a) $t_m = 0$



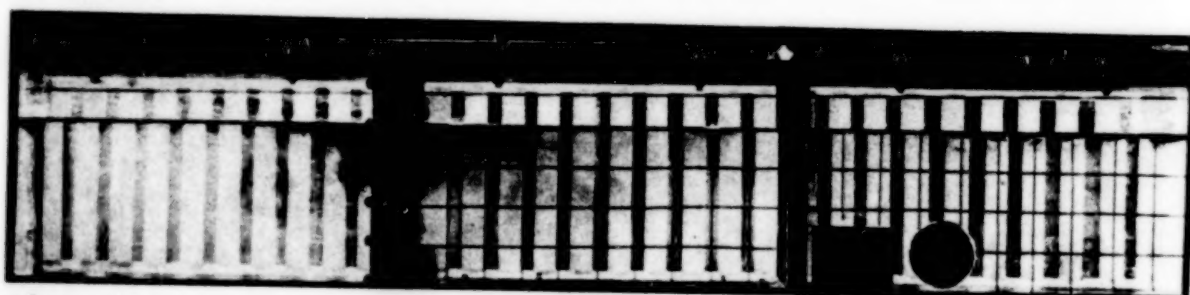
b) $t_m = 15 \text{ s}$



c) $t_m = 30 \text{ s}$

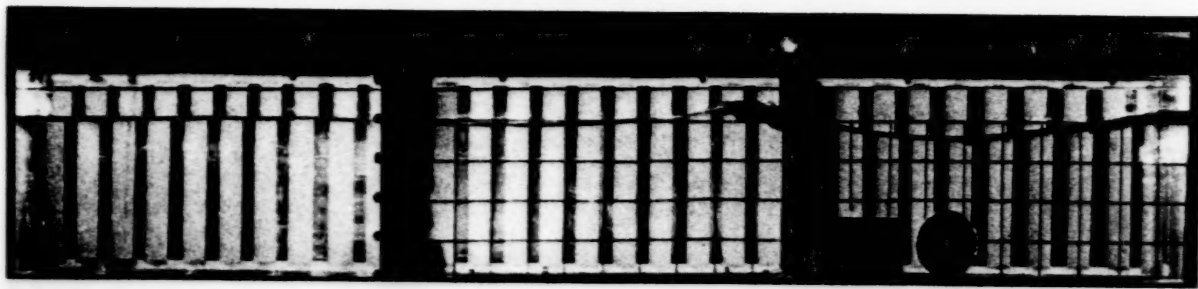


d) $t_m = 60 \text{ s}$

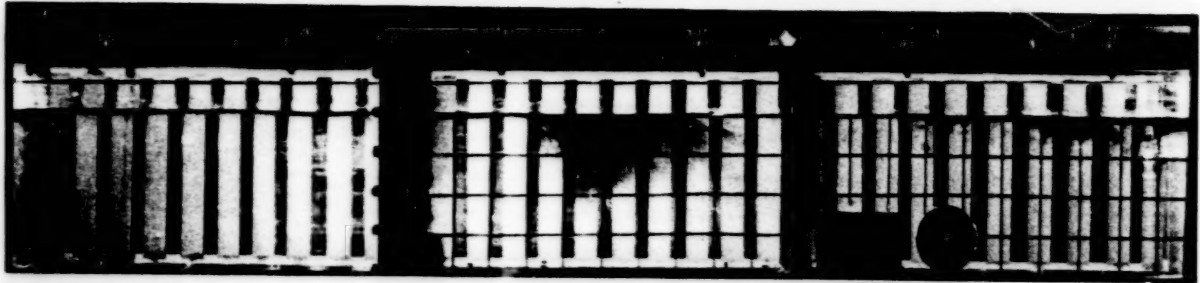


e) $t_m = 120 \text{ s}$

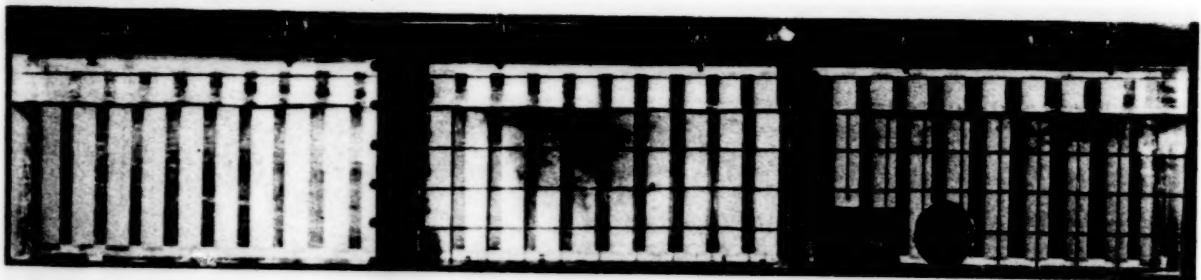
FIGURE V. 27 Dye experiment on breaking-wave turbulence field. wave 5



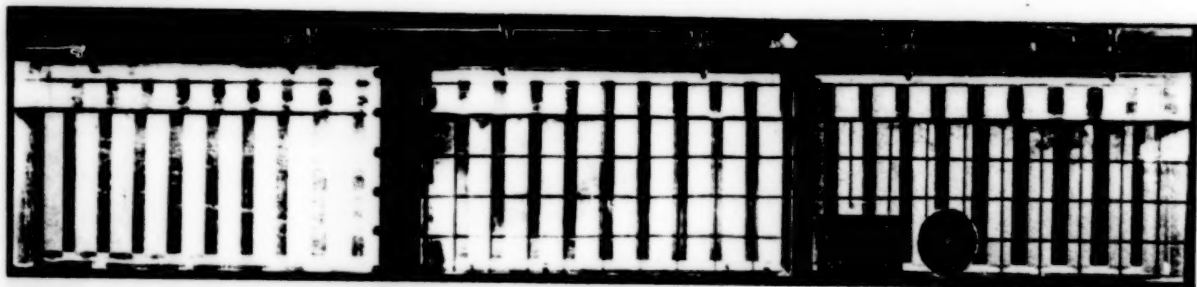
a) $t_m = 0$



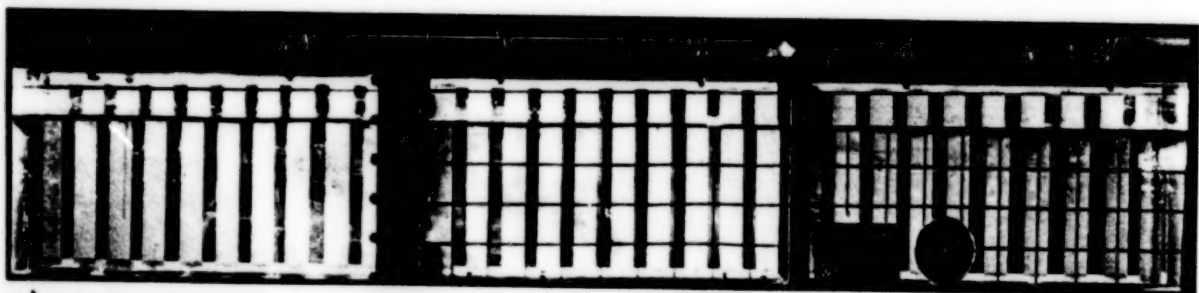
b) $t_m = 15 \text{ s}$



c) $t_m = 30 \text{ s}$

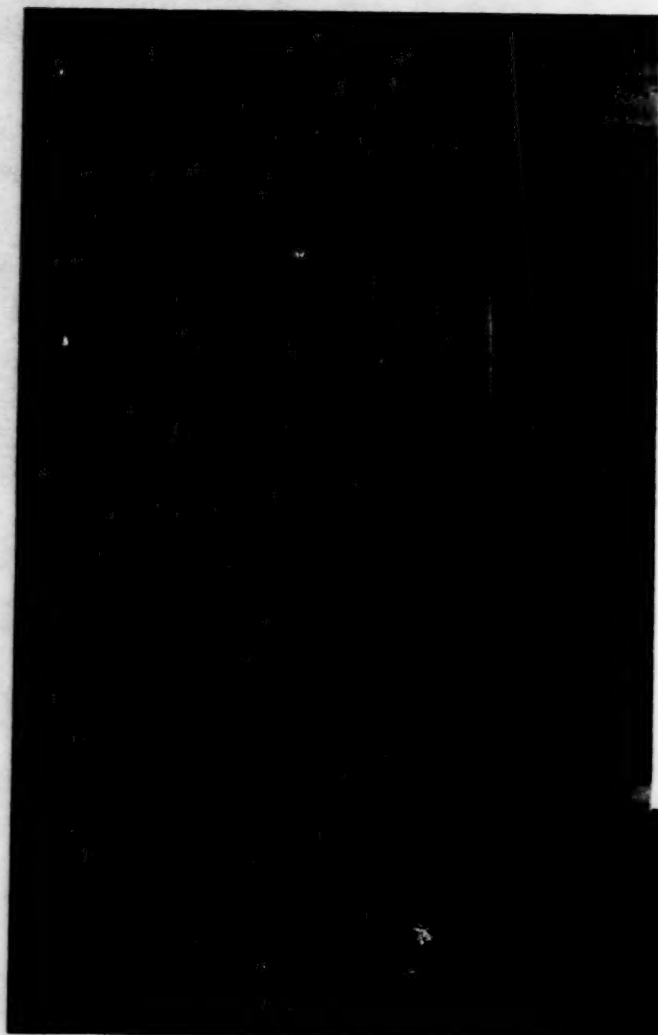


d) $t_m = 60 \text{ s}$

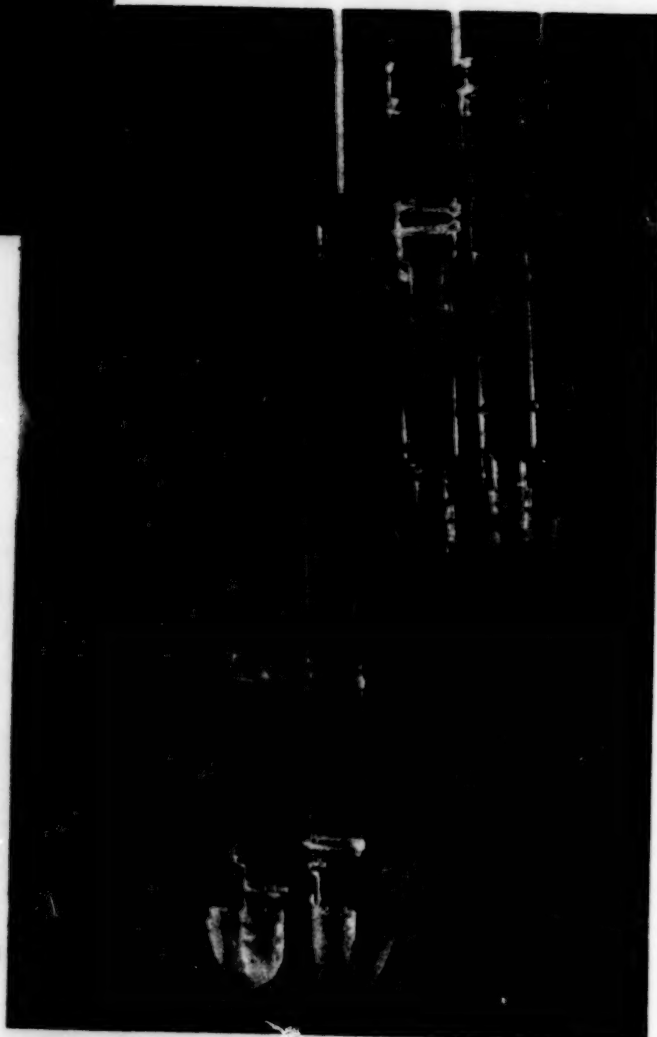


e) $t_m = 120 \text{ s}$

FIGURE V. 28 Dye experiment on breaking-wave turbulence field. wave 7



a) set 1



b) sets 2 and 3

FIGURE V. 29 Sampling devices

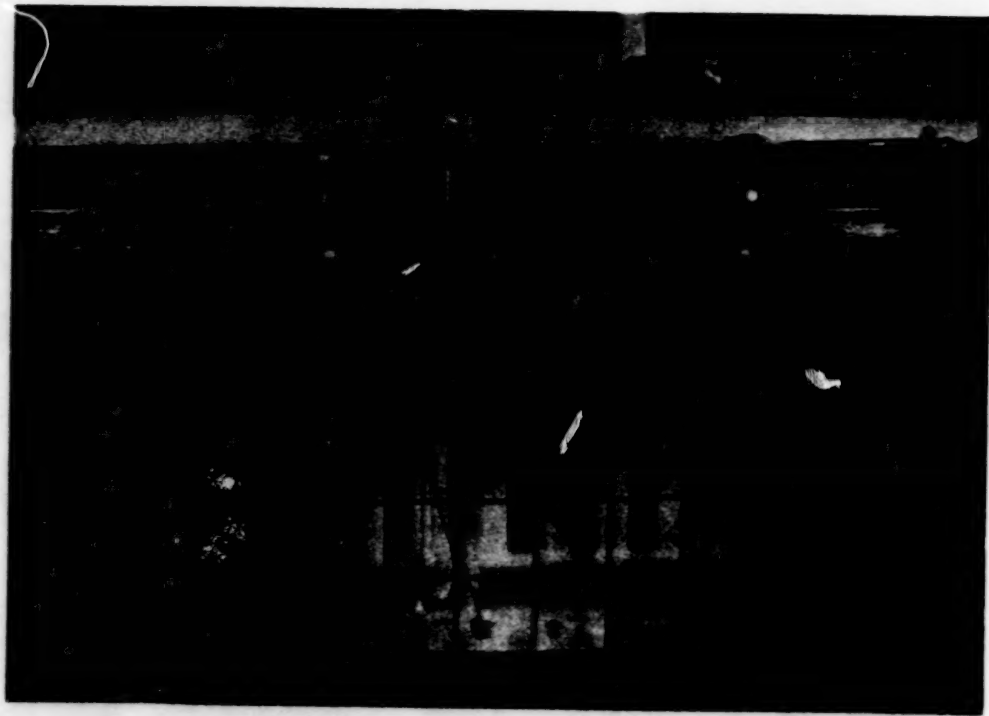


FIGURE V.30 Sampling in oil dispersion experiment

sampling took place while the carriage was moving along the flume, and the (mean) time of sampling t_m after the passage of the breaking wave. The period of sampling resulted in an averaging over a longitudinal trajectory in the droplet cloud. The time of sampling t_m , depth z_g and horizontal sampling trajectory were selected from the results of the dye experiments on the extension of the turbulence field in the course of time for the different wave trains.

Table V.4 surveys the various samples taken in an experiment. Sample "0" is the background sample, taken just before the experiment. The other nine samples were divided into three sets, with three different depths z_g within a set. The lengths of sampling time and the trajectory lengths are equal for all samples within a set. The trajectories were centered around the core of the oil droplet cloud (derived from the dye clouds in the dye experiments).

The trajectory of the first set of samples (1A, B, C) was chosen completely within the droplet cloud. Therefore, the volume of oil in these samples led to oil concentrations in the cloud averaged over a horizontal trajectory. The trajectories of the sampling set 2 and especially 3 incorporated the complete oil droplet cloud. The oil volumes in these samples led to the total amount of dispersed oil at the specific depths below the water surface. The mounted sampling devices of set 1, 2 and 3 are shown in Figure V.29. Figure V.30 gives a more extensive view of sampling sets 2 and 3 during sampling with set 2.

After keeping the samplers in a stationary position for about 2 hours, photographs were taken from the top glass of the samplers (full size on the film negative). The droplet size distributions in the range 50 to 2000 μm were derived from droplet-counting while projecting the negatives on a screen. After a stationary positioning of about 20 hours, the samplers were placed under the microscope. The applied enlargement was usually 72x for droplet counting in the size range 3 to 100 μm . (It is discussed in Section A.4 that distortion of the distribution due to coagulation of droplets in the sampler is negligible).

Table V.4 Oil-water samples in experiments with samplers

sample	depth below water surface z_s (m)	mean sam- pling time t_m (s)	period of sampling t_m (s)	sampling trajectory length $u_c = 5$ cm/s $u_c = 3$ cm/s	
0	variable	< 0			
1A)	0.05	} 15	10 - 20	0.5	n.a.
1B) set 1	0.10				
1C)	0.20				
2A)	0.10	} 60	45 - 75	1.5	0.9
2B) set 2	0.20				
2C)	0.40				
3A)	0.10	} 150	120 - 180	3.0	1.8
3B) set 3	0.20				
3C)	0.40				

Evidently, the number of droplets in a sampler depends on the droplet concentration in the cloud averaged over the sampling trajectory, and on the exchanged water volume V_g during the length of sampling time. (See Appendix A.2.3). The exchanged volume V_g in a sampler was derived from the density of the water in the device measured by a weighing procedure, relative to the known density of the brine originally in the device, $\rho_{\text{brine}} = 1150 \text{ kg/m}^3$, and the known density of the water in the flume, $\rho_w = 1025 \text{ kg/m}^3$.

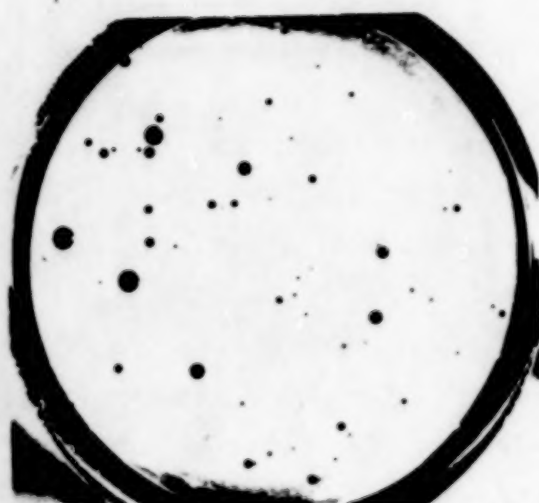
V.6.3 The Measurements

Table V.3 summarizes the Oil Flume dispersion experiments executed with the oil droplet samplers. Illustrations and results are given in Figures V.31 to V.84, for all oil droplet samples taken.

The photographs in the Figures V.31 to V.84 show the surfaced oil droplets in the samplers with $d_o \geq 100 \mu\text{m}$. Air bubbles (circles) can be distinguished easily from oil droplets (dots). The results of a set of samples (nA, nB, nC with $n = 1, 2$ or 3) were gathered in one figure. The droplet size distributions are given in a graph, for each set of samples. The droplet sizes were divided into size classes $0.7 d_o$ to $1.4 d_o$ centered on the logarithmic scale around the droplet size d_o . The number of droplets in a size class, $N(d_o)$, was determined by counting. The results were transformed to $N(d_o)$ per litre (= concentration) for the first set of samples 1A, B, C, because these samples were withdrawn completely within the droplet cloud in the flume. The entire oil droplet cloud was traversed during set 2 and set 3 sampling. Therefore, the results of the set 2 and set 3 samples could be transformed to the number of droplets $N(d_o)$ in a horizontal "flume slice" on the depth of measurement (slice thickness was taken $10^{-3}h$), by multiplication of the droplet numbers per exchanged unit volume (in m^3) in the set 2 and set 3 samples with the trajectory length (see Table V.4), flume width (= 0.5 m) and slice thickness (= $0.43 \times 10^{-3} \text{ m}$).

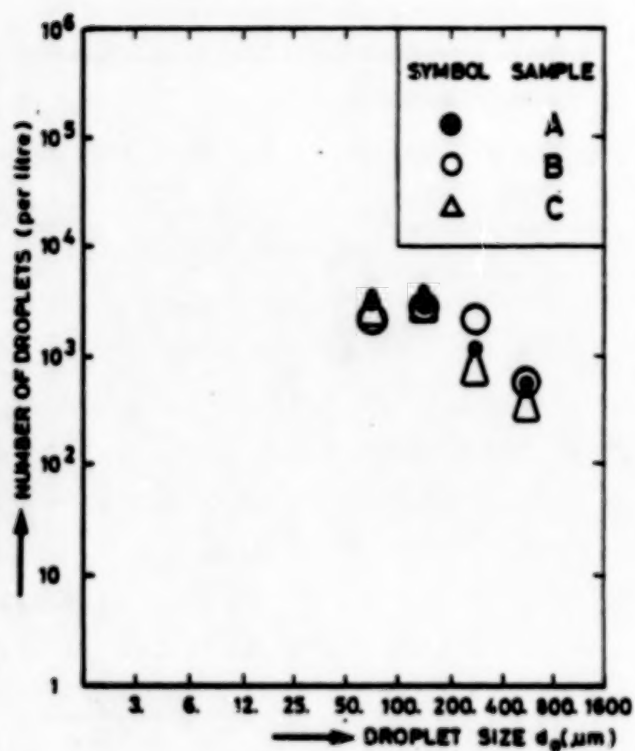
Note: the number of droplets $N(d_o)$ in the Figures V.31 to V.84 are rela-

RUN	S2	PB ₀
SAMPLES	1	A, B, C
WAVE	2	T _w = 1.25 s
TEMPERATURE	15	°C
OIL LAYER	0.6	mm
WATERDEPTH	0.43	m
SMALL-SCALE EXPERIMENT		



B

C



0 1cm

FIG. V. 31 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



[a]

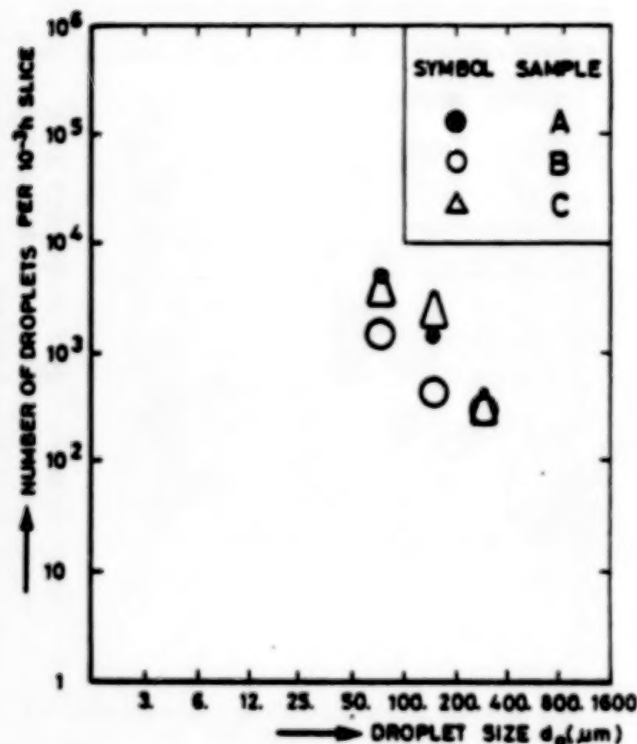


[b]



[c]

RUN S2 PB₀
 SAMPLES 2 A,B,C
 WAVE 2 T_w=1.25 s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1cm

FIGURE V. 32 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

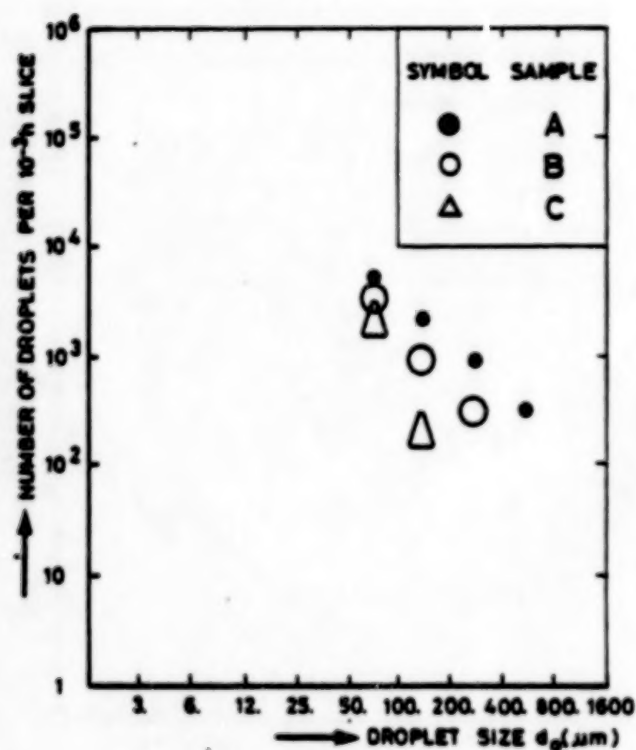


B



C

RUN S2 PB_0
 SAMPLES 3 A, B, C
 WAVE 2 $T_W = 1.25$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1 cm

FIG. V. 33 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A



B

C

RUN S3 PB₁₀
 SAMPLES 1 A, B, C
 WAVE 2 $T_w = 1.25$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

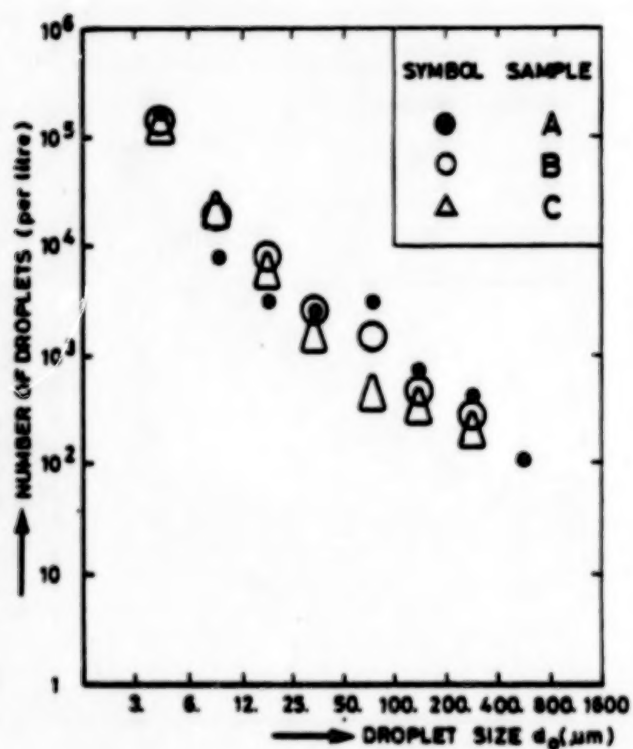


FIG. V. 34 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.

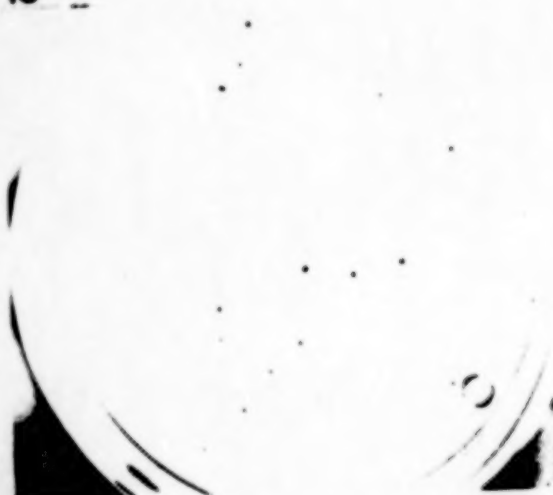


A

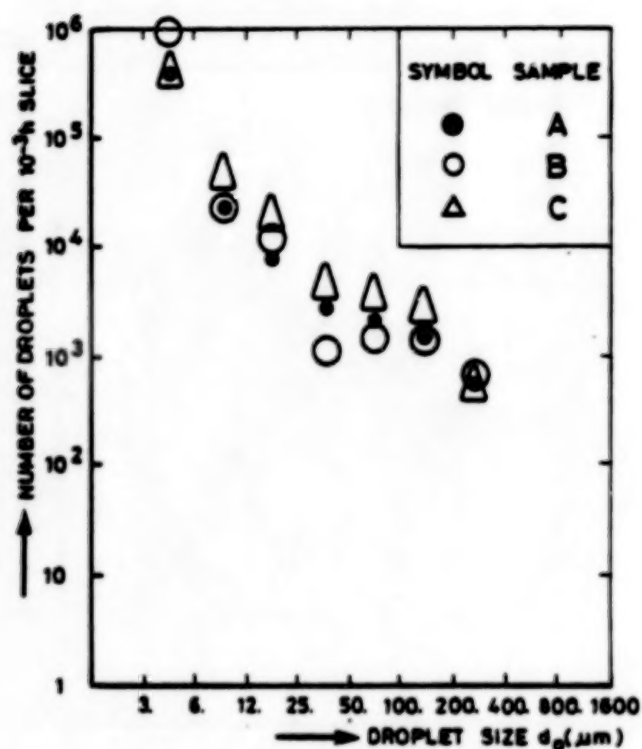


B

C



RUN S3 PB₁₀
 SAMPLES 2 A,B,C
 WAVE 2 T_w = 1.25 s
 TEMPERATURE 15 °C
 OIL LAYER 0.5 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1cm

FIG. V. 35 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

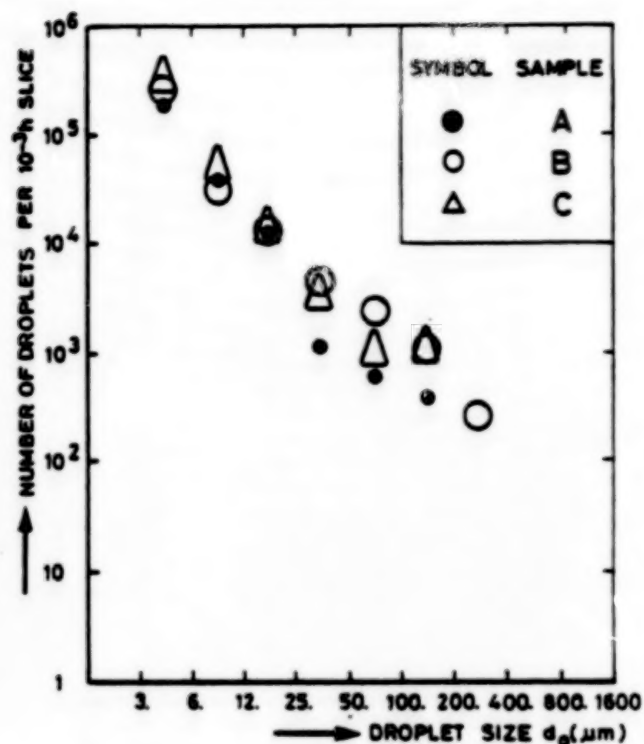


B

C



RUN S3 PB₁₀
 SAMPLES 3 A, B, C
 WAVE 2 T_w = 1.25 s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1cm

FIG. V. 36 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.

RUN S4 Eko
 SAMPLES 1 B, C
 WAVE 2 $T_w = 1.25$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



B

C

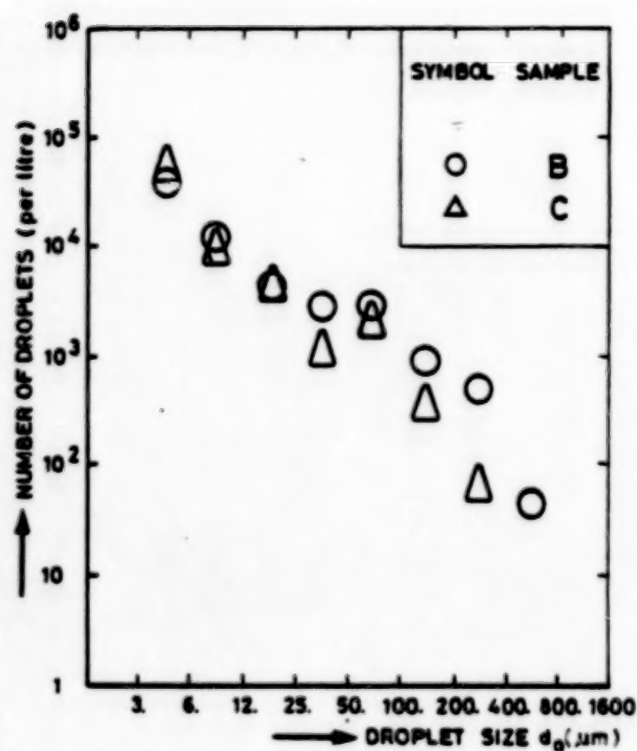


FIG. V. 37 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

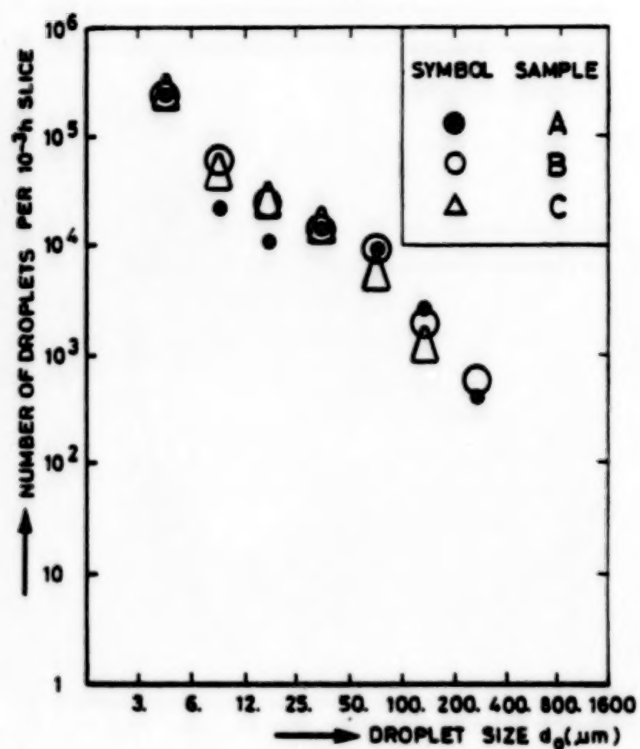


B



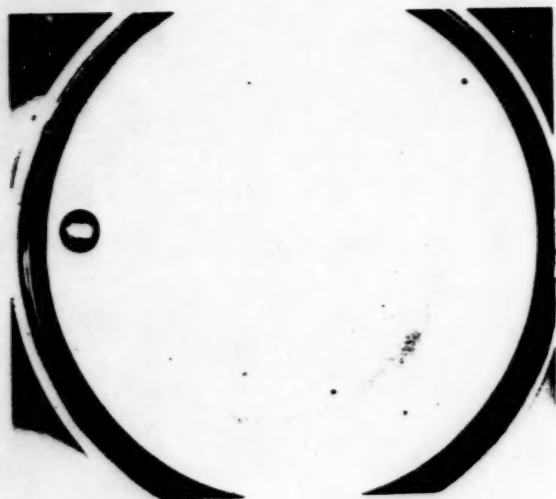
C

RUN S4 Eko
 SAMPLES 2 A,B,C
 WAVE 2 $T_w = 1.25$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

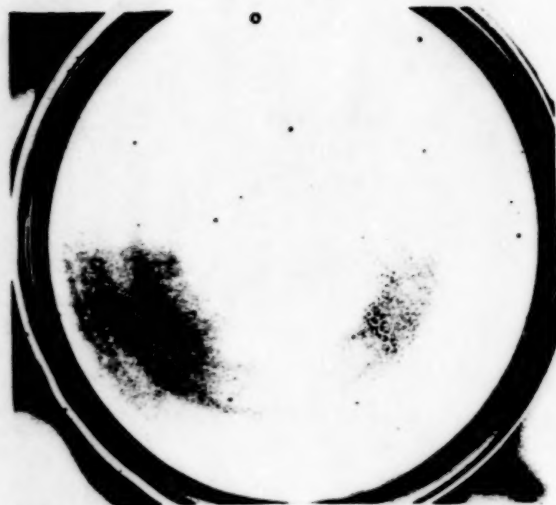


0 1cm

FIG. V. 38 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

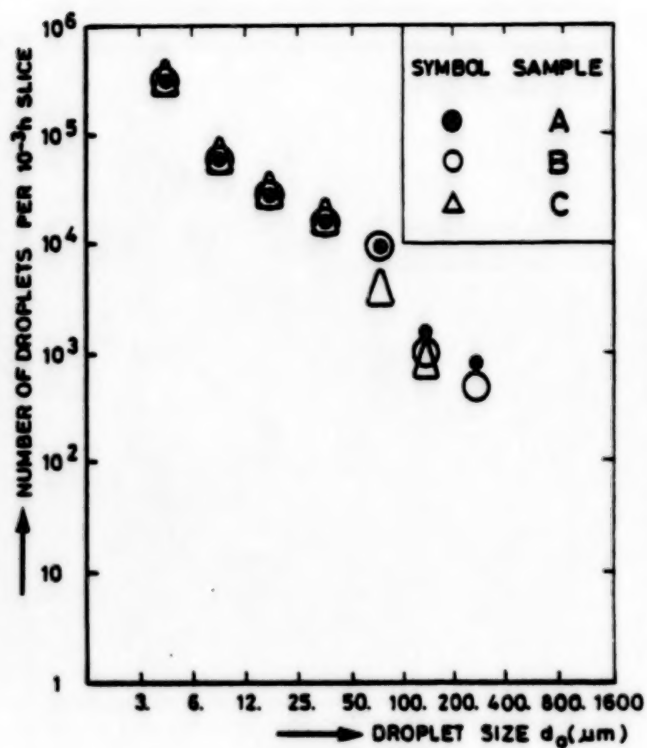


B



C

RUN S4 Eko
 SAMPLES 3 A, B, C
 WAVE 2 $T_w = 1.25$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1cm

FIG. V. 39 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.

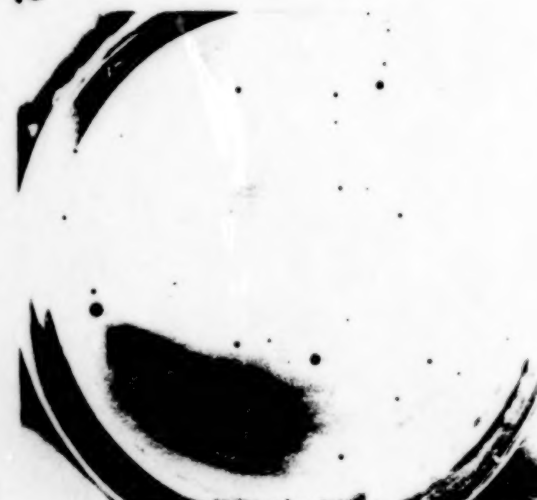


A

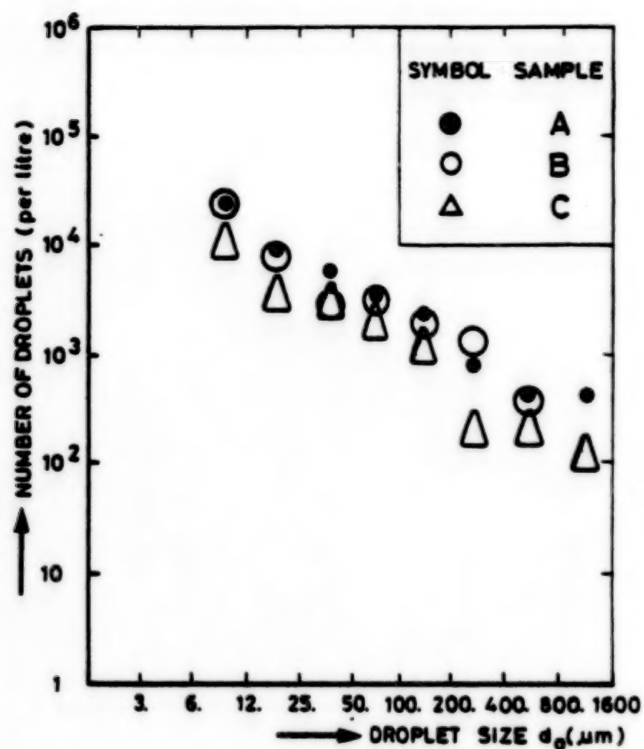


B

C



RUN S7 PB₁₀
 SAMPLES 1 A,B,C
 WAVE 3 T_w = 1.2 s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1cm

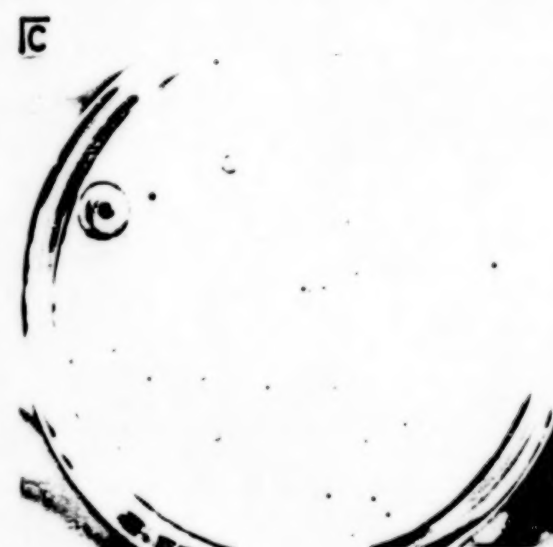
FIG. V.40 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A



B



C

RUN S7 PB₁₀
 SAMPLES 2 A,B,C
 WAVE 3 T_w = 1.2 s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

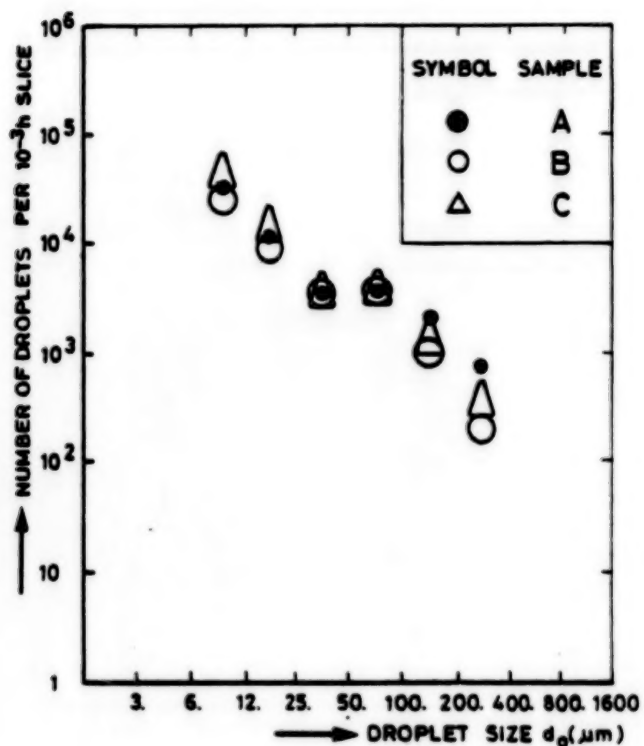


FIG. V. 41 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

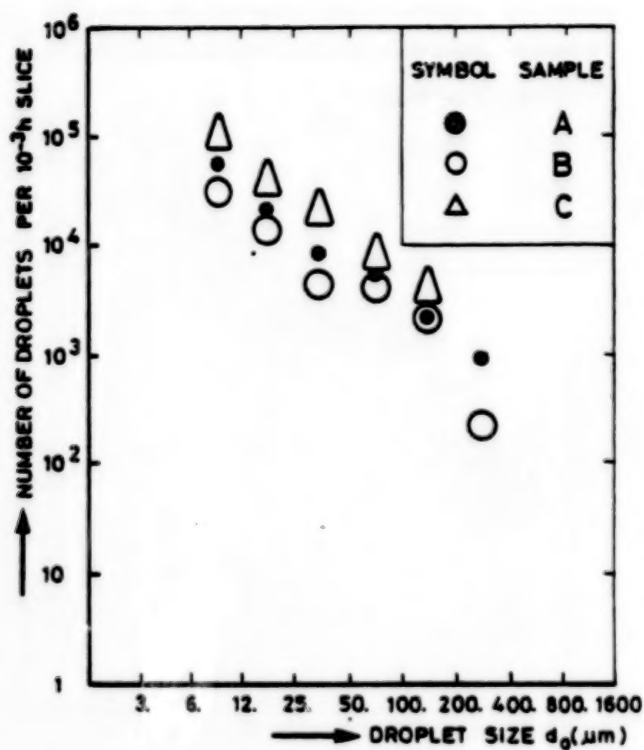


B



C

RUN S7 PB₁₀
 SAMPLES 3 A,B,C
 WAVE 3 T_w = 1.2 s
 TEMPERATURE 15 °C
 OIL LAYER 0.5 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1cm

FIG. V. 42 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

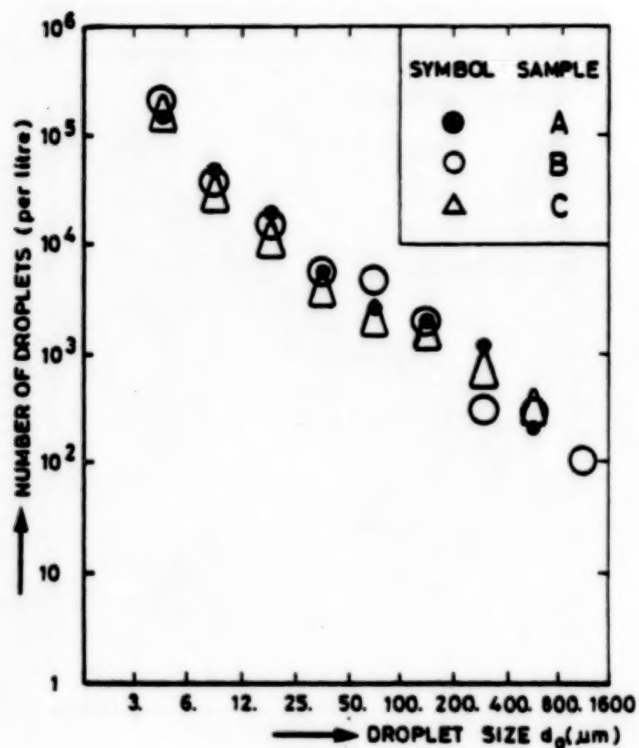


B

C



RUN S8 PB₀
 SAMPLES 1 A,B,C
 WAVE 3 T_w = 1.2 s
 TEMPERATURE 15 °C
 OIL LAYER 0.5 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1cm

FIG. V. 43 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

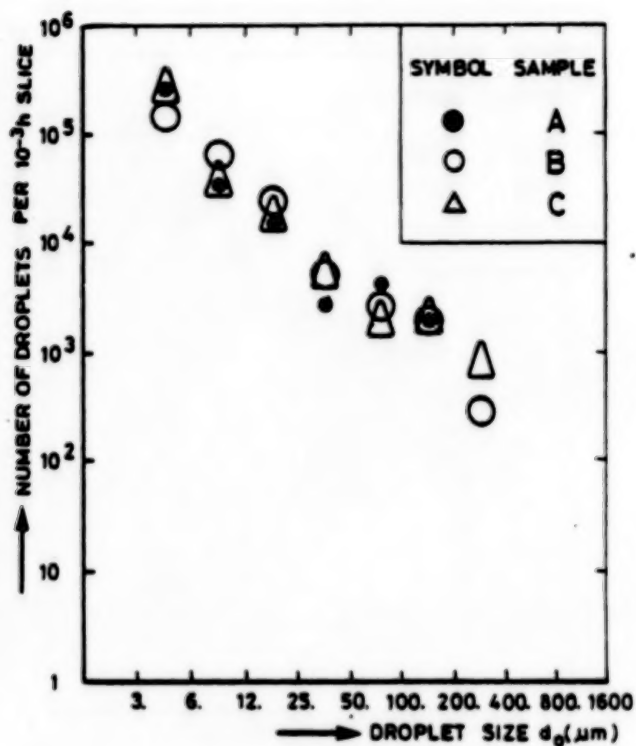


B



C

RUN S8 PB₀
 SAMPLES 2 A,B,C
 WAVE 3 T_w = 1.2 s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43m
 SMALL-SCALE EXPERIMENT



0 1cm

FIG. V. 44 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

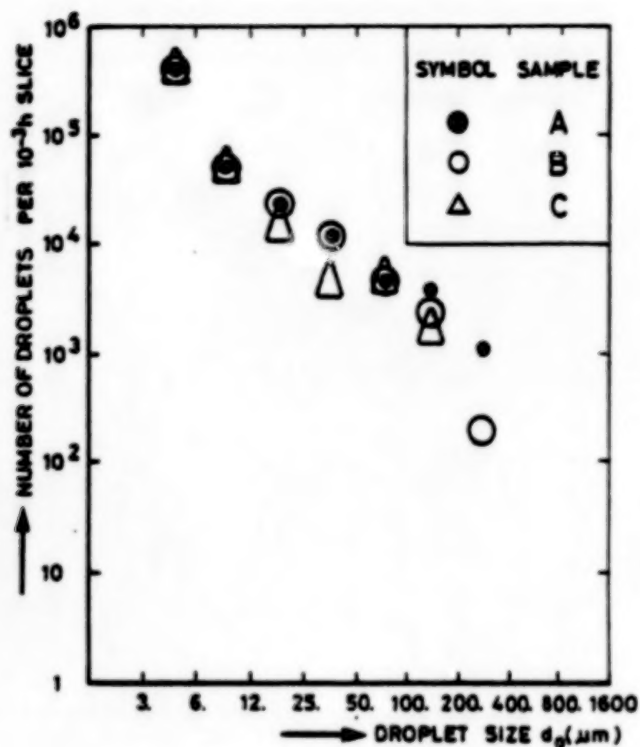


B



C

RUN S8 PB₀
 SAMPLES 3 A,B,C
 WAVE 3 T_w= 1.2 s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1cm

FIG. V. 45 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



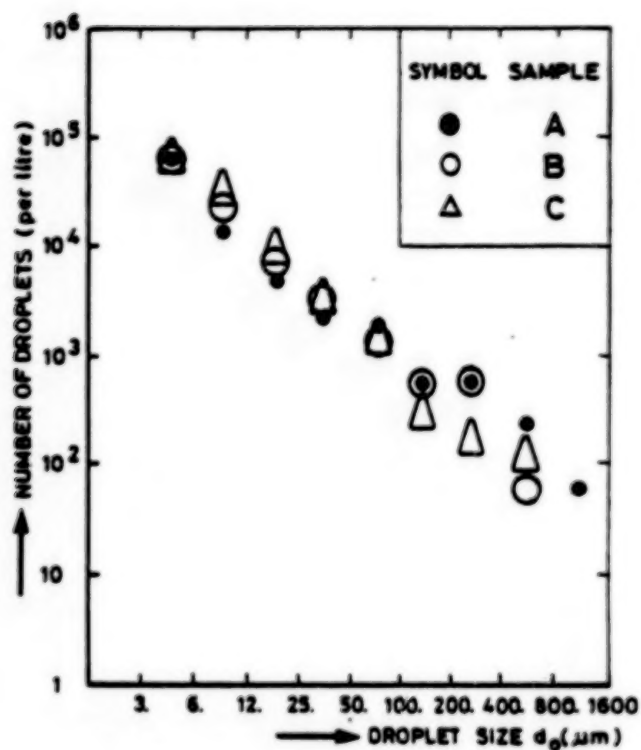
A

RUN S9 PB₀
 SAMPLES 1 A,B,C
 WAVE 3 T_w = 1.2 s
 TEMPERATURE 15 °C
 OIL LAYER 0.2 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



B

C



0 1cm

FIG. V. 46 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



RUN S9. PB_0
 SAMPLES 2 A, B, C
 WAVE 3 $T_w = 1.2$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.2 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

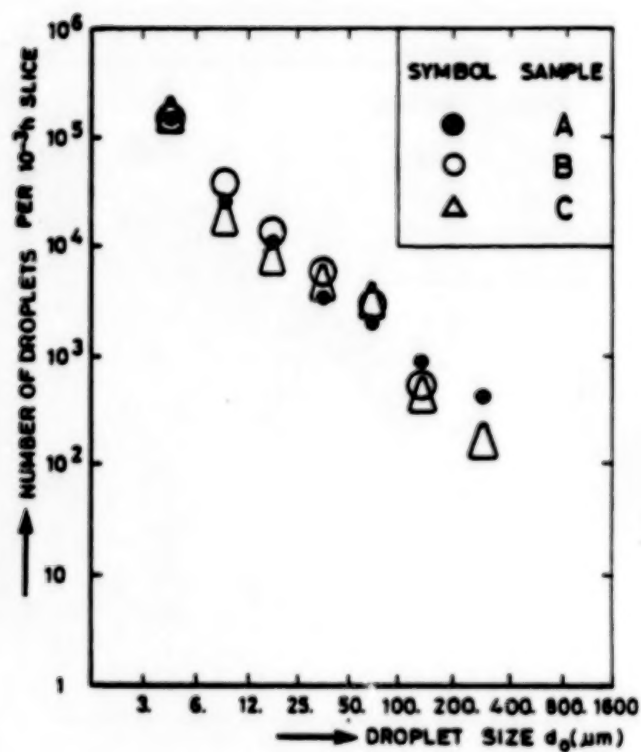


FIG. V. 47 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

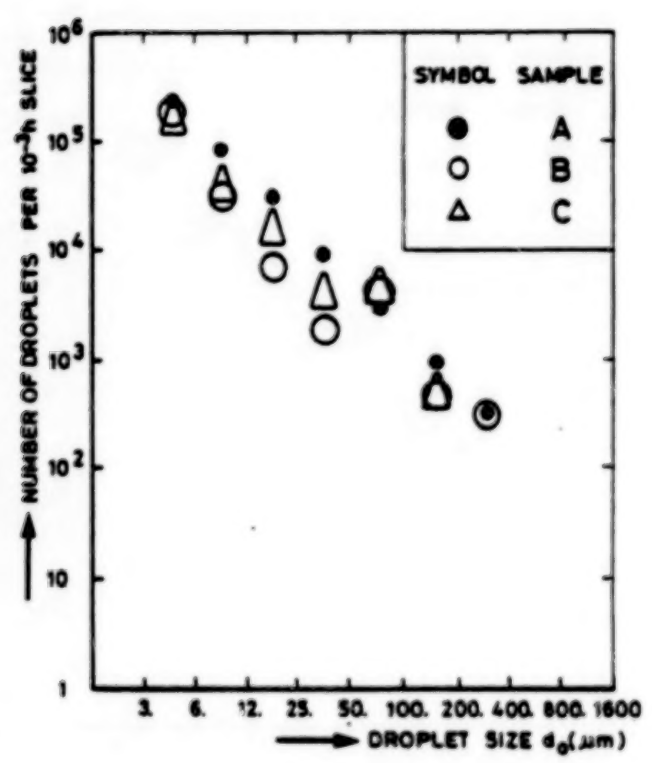


B

C



RUN S9 PB₀
 SAMPLES 3 A,B,C
 WAVE 3 T_w = 1.2 s
 TEMPERATURE 15 °C
 OIL LAYER 0.2 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1cm

FIG. V. 48 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A



B



C

RUN S10 PB₀
 SAMPLES 1 A,B,C
 WAVE 3 T_w = 1.2 s
 TEMPERATURE 15 °C
 OIL LAYER 1.2 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

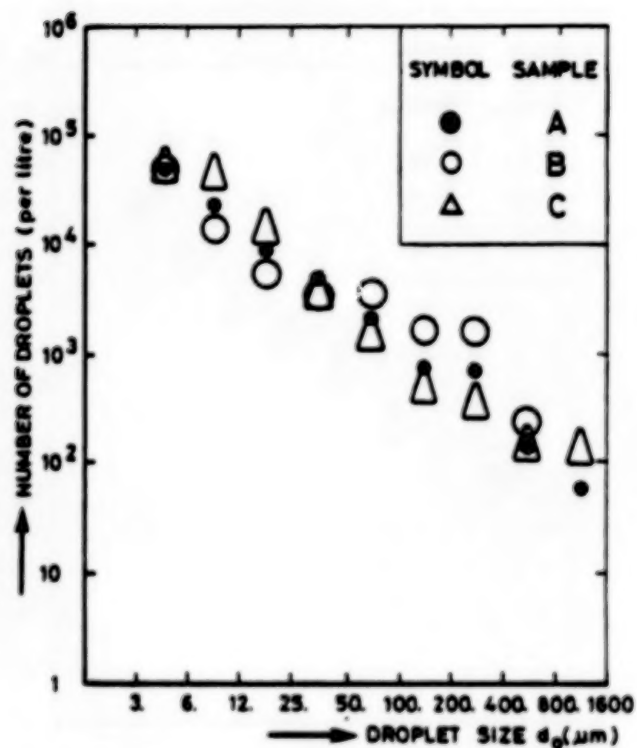


FIG. V.49 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

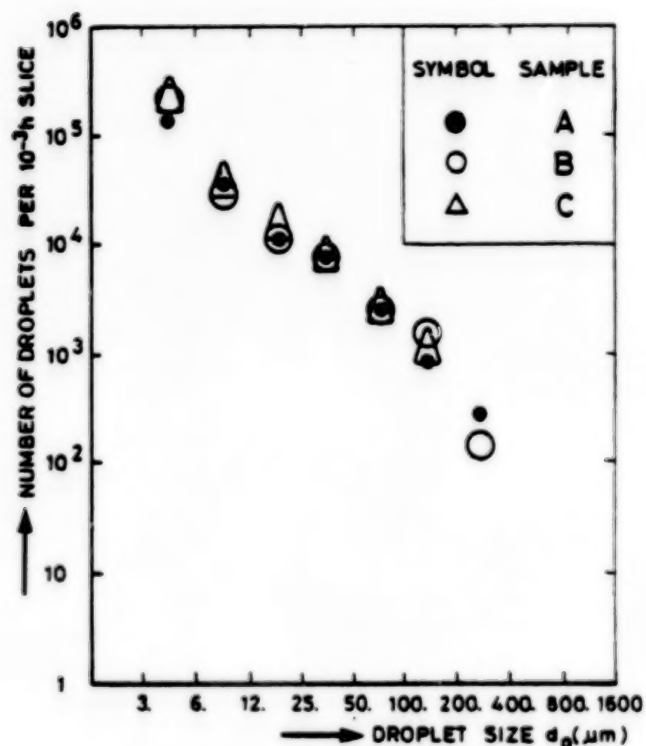


B

C



RUN S10 PB_0
 SAMPLES 2 A, B, C
 WAVE 3 $T_w = 1.2$ s
 TEMPERATURE 15 °C
 OIL LAYER 1.2 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1 cm

FIG. V.50 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

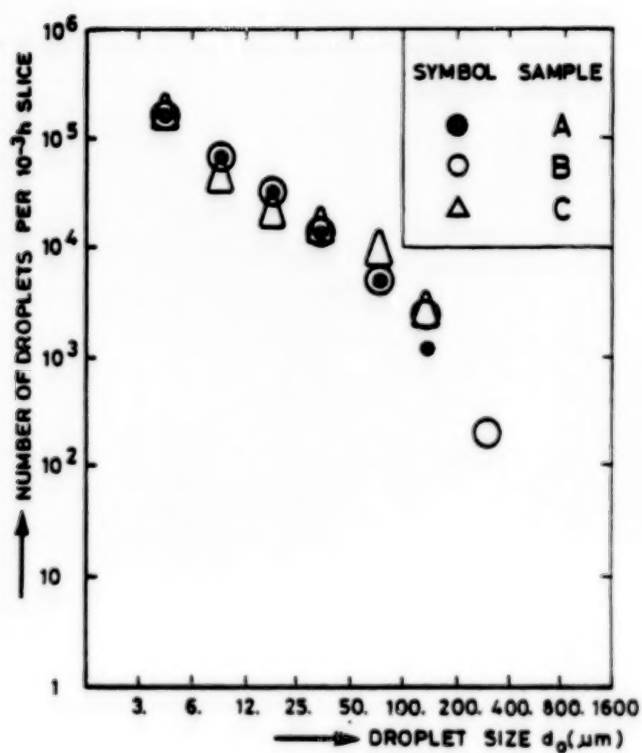


B



C

RUN S10 PB₀
 SAMPLES 3 A, B, C
 WAVE 3 T_w = 1.2 s
 TEMPERATURE 15 °C
 OIL LAYER 1.2 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

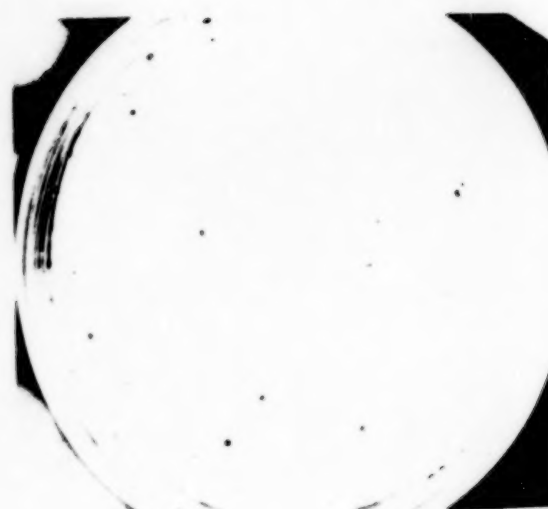


0 1cm

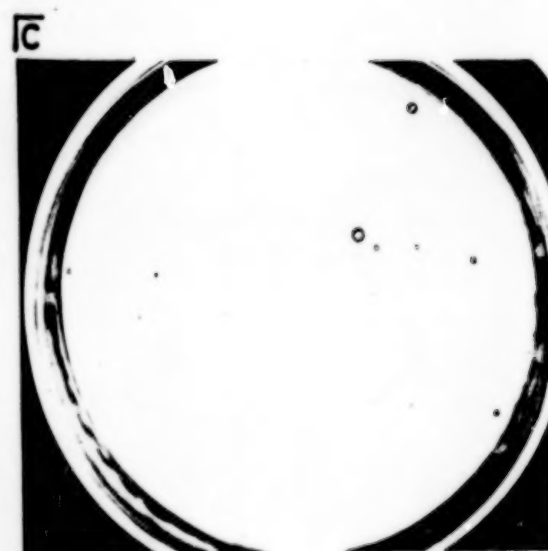
FIG. V. 51 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A



B



C

RUN S11 Eko
 SAMPLES 1 A,B,C
 WAVE 3 $T_w = 1.2$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43m
 SMALL-SCALE EXPERIMENT

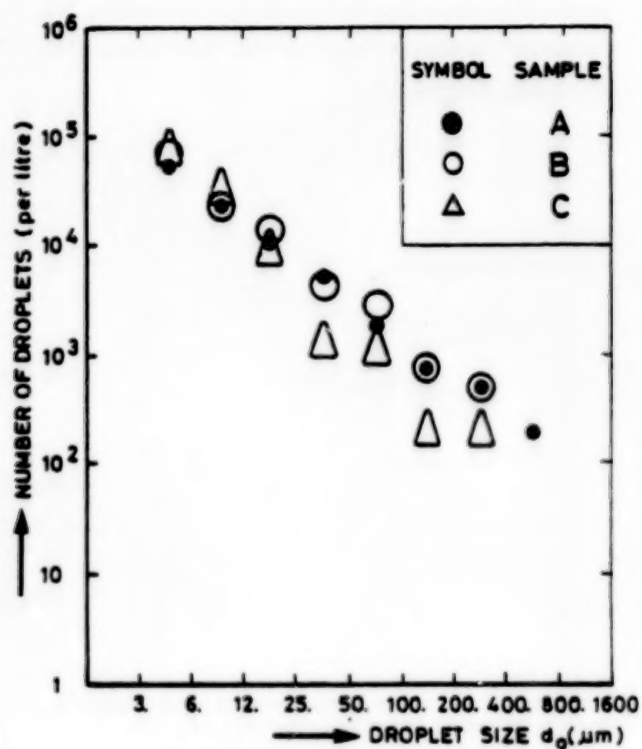
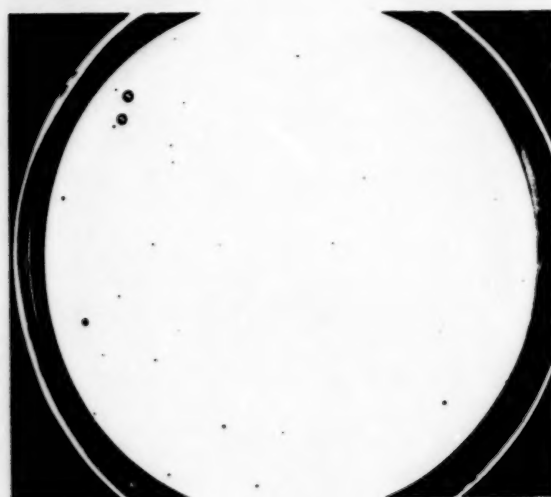
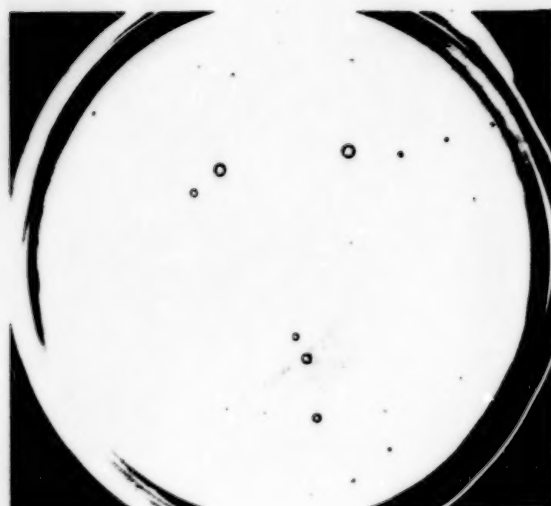


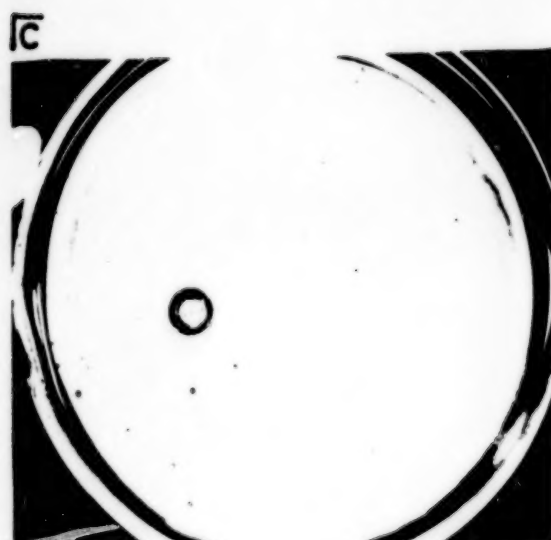
FIG. V. 52 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

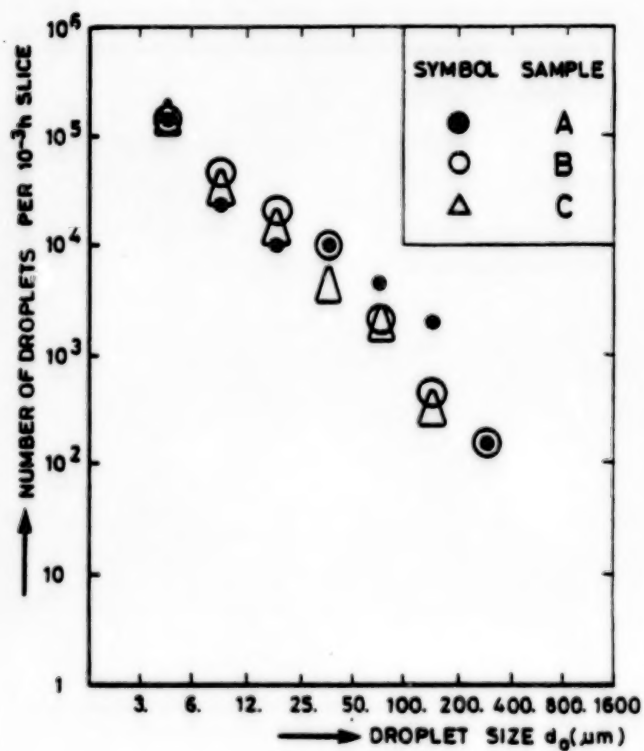


B



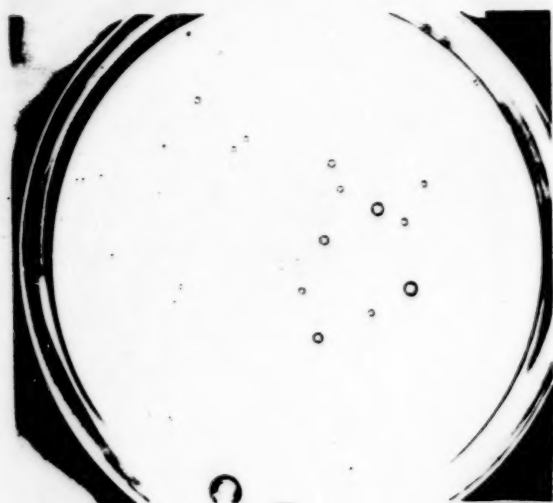
C

RUN S11 Eko
 SAMPLES 2 A,B,C
 WAVE 3 $T_w = 1.2$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

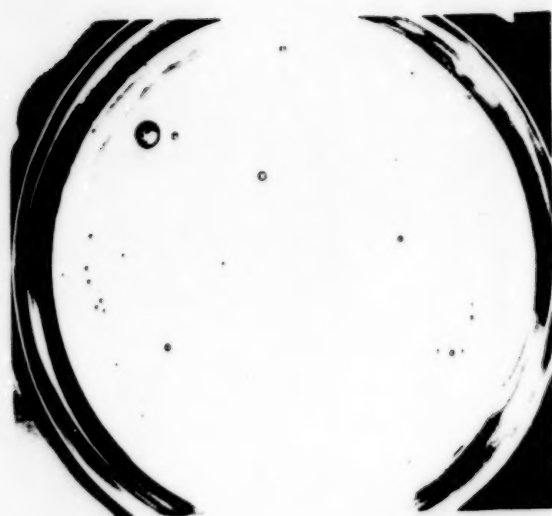


0 1cm

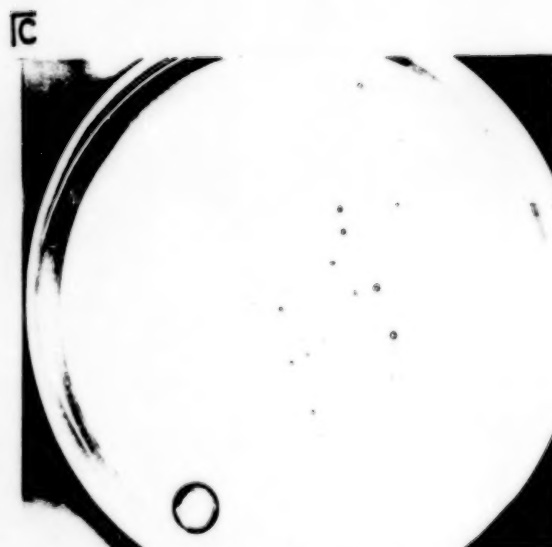
FIG. V. 53 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

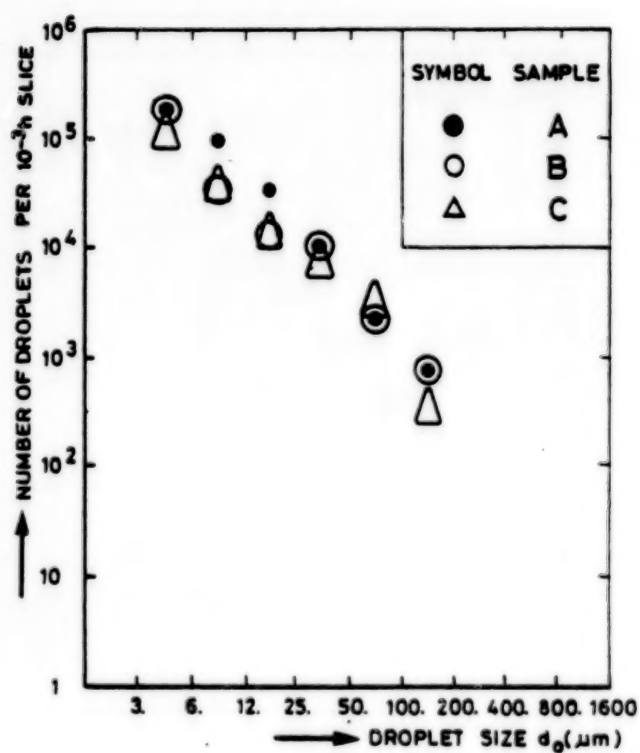


B



C

RUN S11 Eko
 SAMPLES 3 A, B, C
 WAVE 3 $T_W = 1.2$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

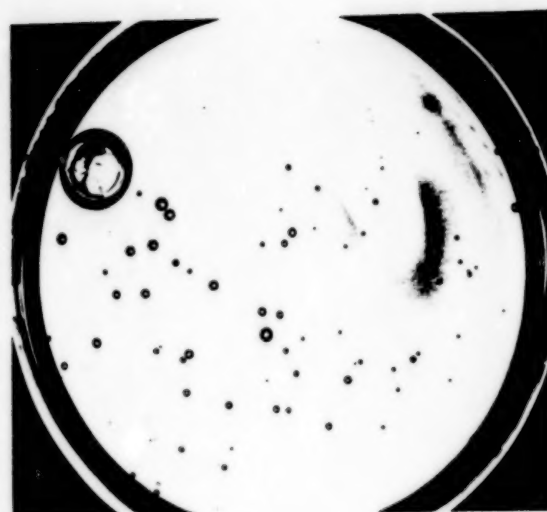


0 1cm

FIG. V. 54 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

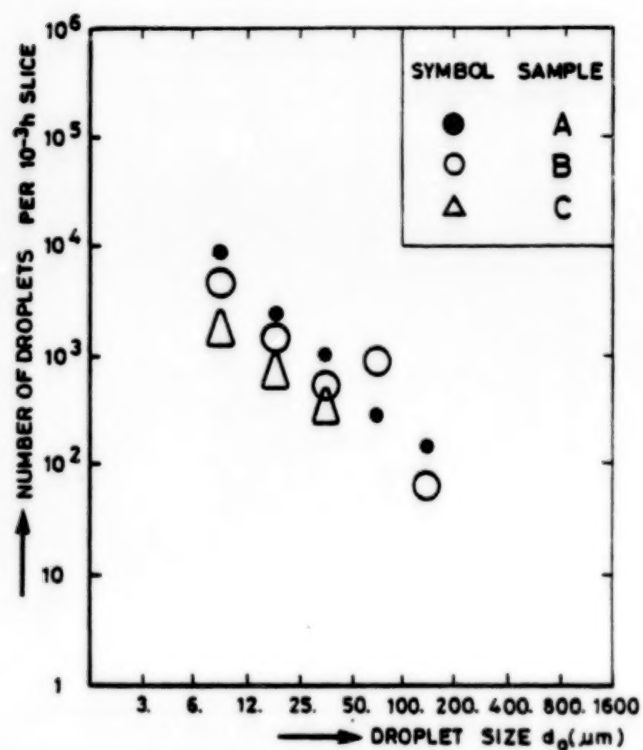


B



C

RUN S12 Eko
 SAMPLES 1 A,B,C
 WAVE 7 $T_w = 0.8$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1 cm

FIG. V. 55 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.

no visible droplets
on photographs

RUN S12 Eko
SAMPLES 2 A,B,C
WAVE 7 $T_w = 0.8$ s
TEMPERATURE 15 °C
OIL LAYER 0.6 mm
WATERDEPTH 0.43 m
SMALL-SCALE EXPERIMENT

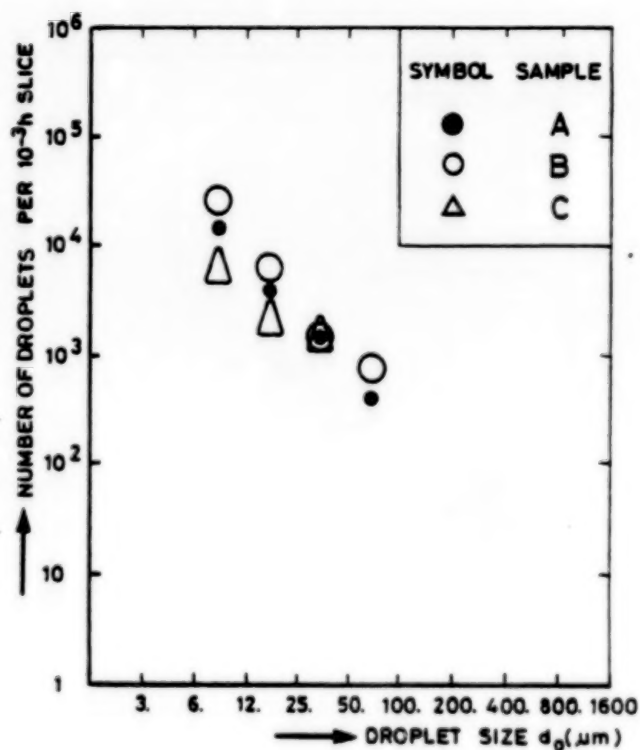
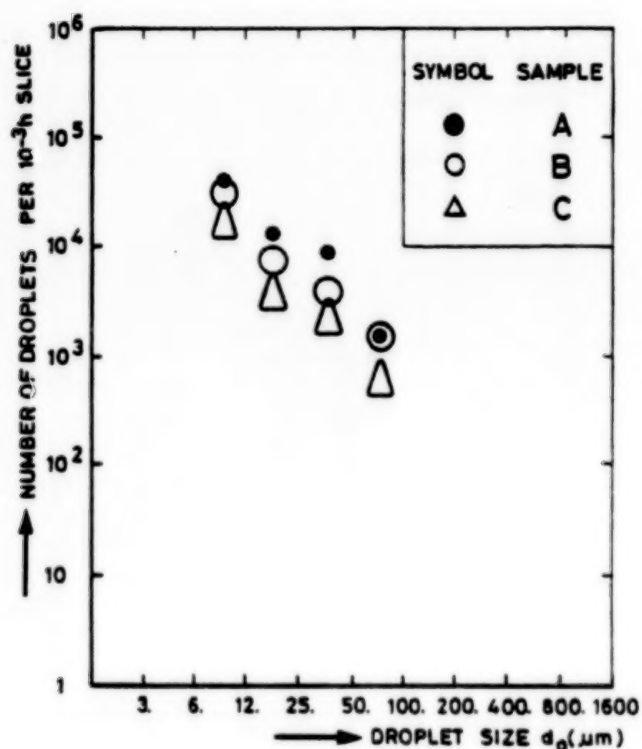


FIG. V. 56 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.

no visible droplets
on photographs

RUN	S12	Eko
SAMPLES	3	A, B, C
WAVE	7	$T_w = 0.8$ s
TEMPERATURE		15 °C
OIL LAYER		0.6 mm
WATERDEPTH		0.43 m

SMALL-SCALE EXPERIMENT



0 1cm

FIG. V. 57 OIL DROPLETS. DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

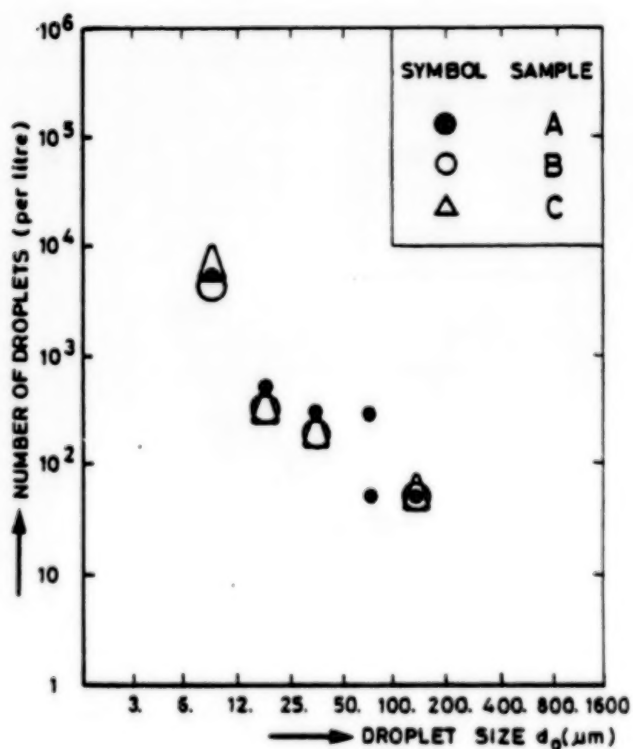


B



C

RUN S13 PB₀
 SAMPLES 1 A,B,C
 WAVE 7 T_w = 0.8 s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

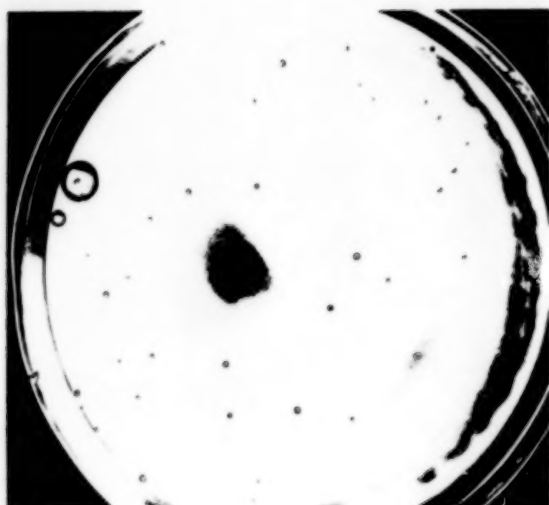


0 1cm

FIG. V. 58 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

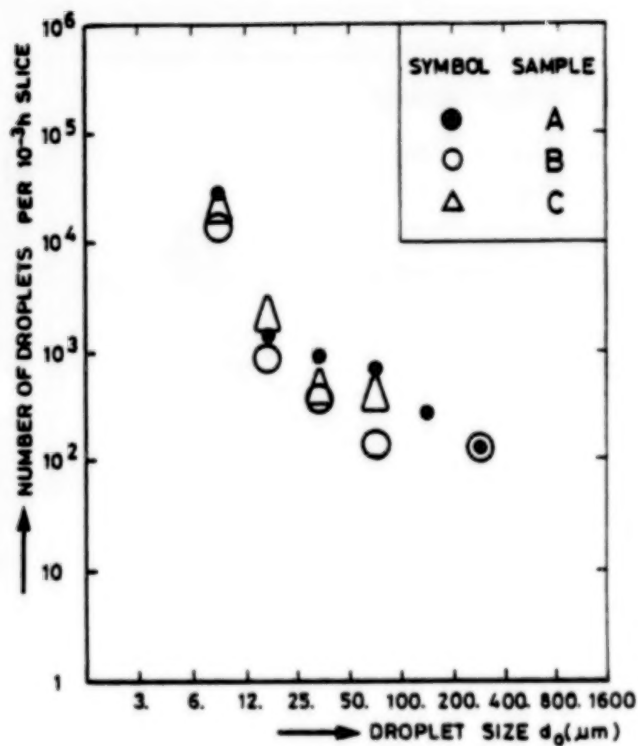


B



C

RUN S13 PB_0
 SAMPLES 2 A,B,C
 WAVE 7 $T_w = 0.8$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1cm

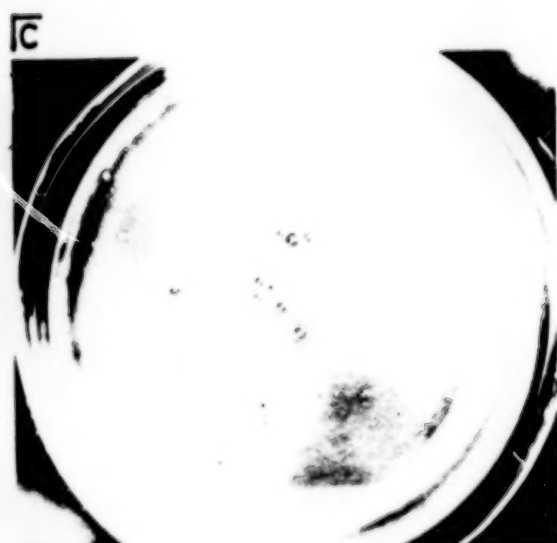
FIG. V. 59 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

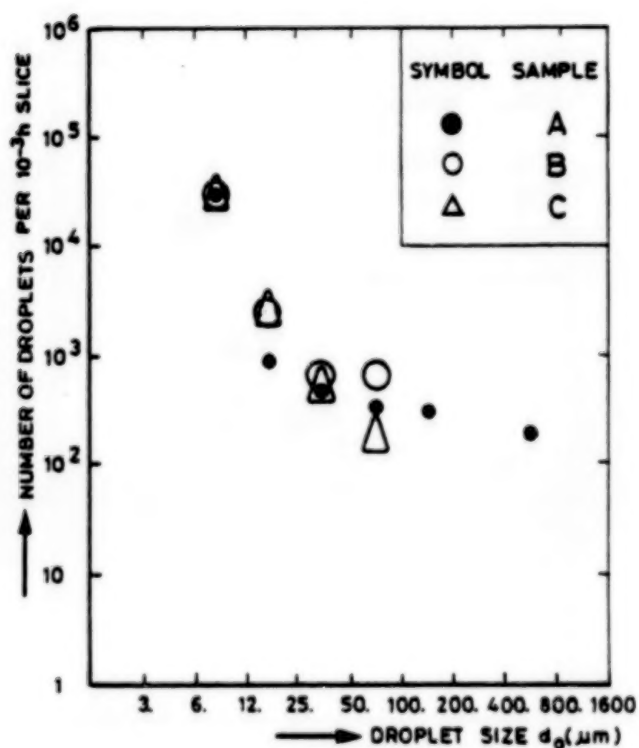


B



C

RUN S13 PB₀
 SAMPLES 3 A,B,C
 WAVE 7 T_w = 0.8 s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43m
 SMALL-SCALE EXPERIMENT



0 1cm

FIG. V. 60 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

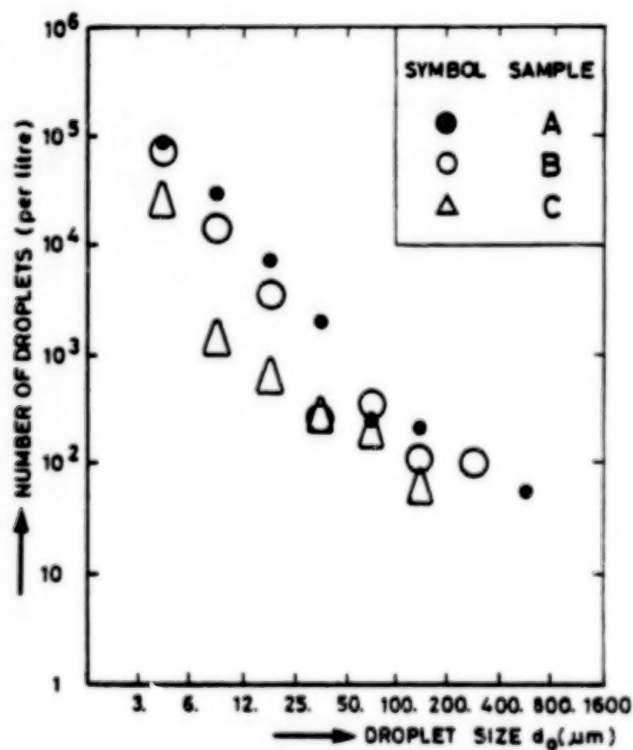


B



C

RUN S14 PB_0
 SAMPLES 1 A, B, C
 WAVE 5 $T_w = 1.0$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

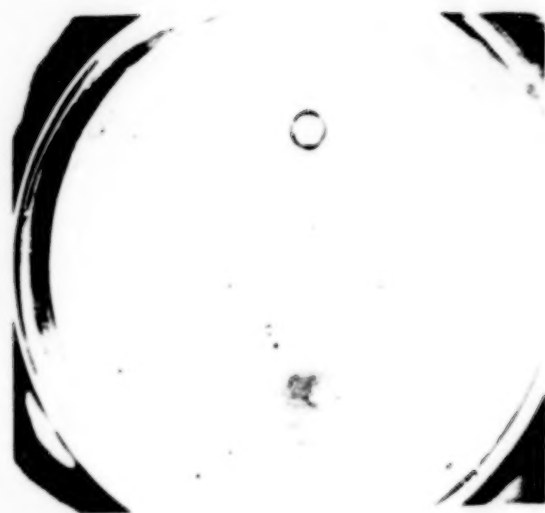


0 1 cm

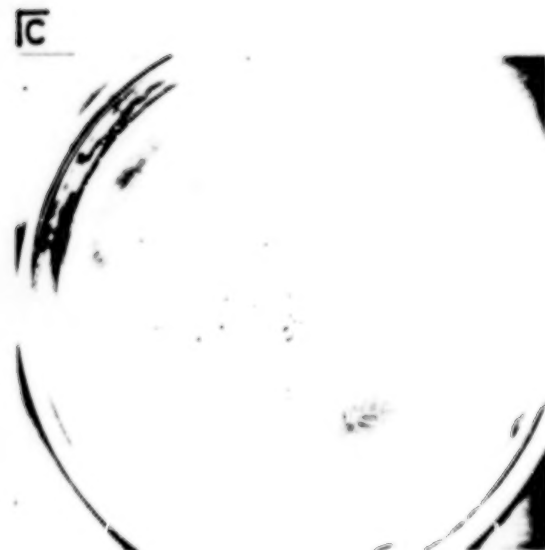
FIG. V. 61 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A



B



C

RUN S 14 PB_0
 SAMPLES 2 A, B, C
 WAVE 5 $T_W = 1.0$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

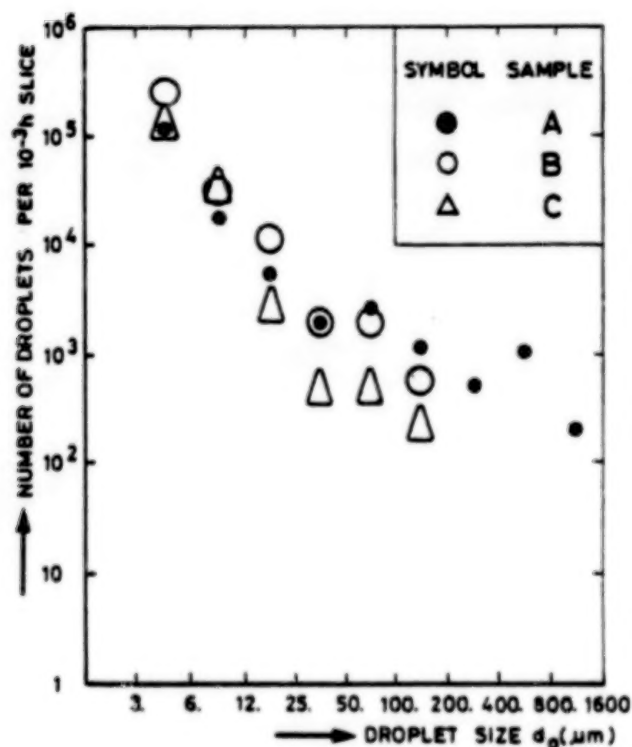
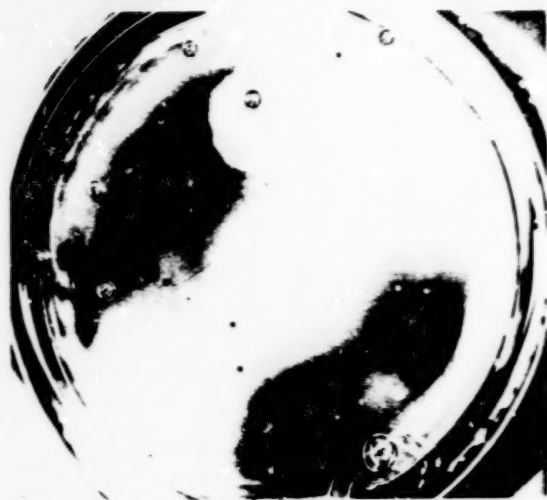


FIG. V. 62 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

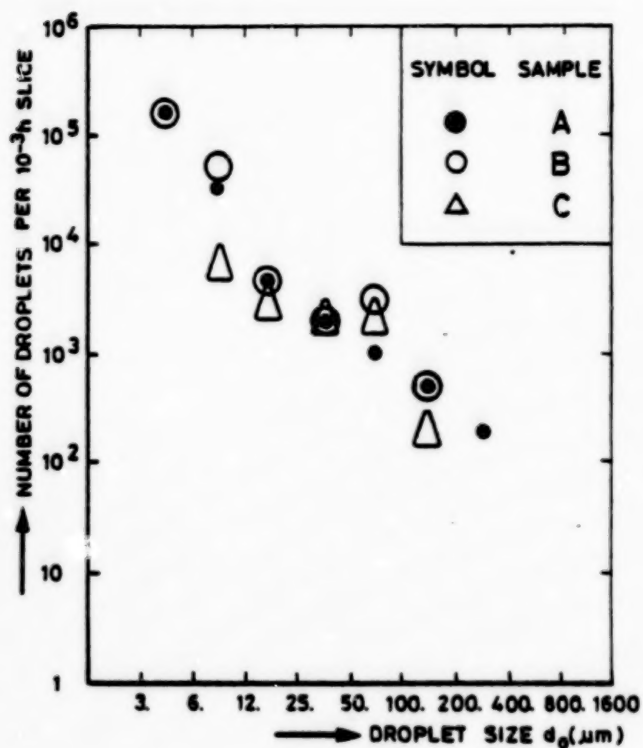


B



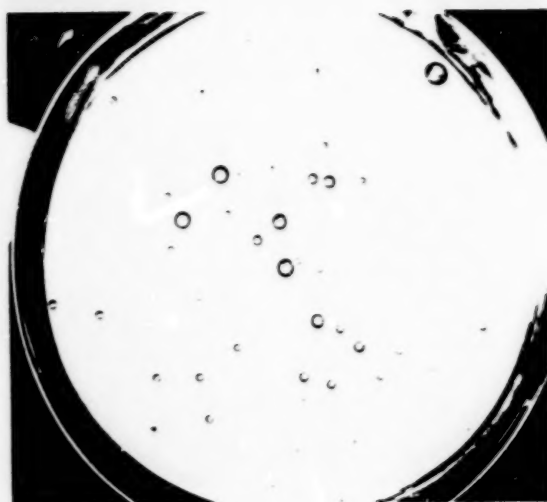
C

RUN S 14 PB_0
 SAMPLES 3 A,B,C
 WAVE 5 $T_w = 1.0$ s
 TEMPERATURE 15°C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

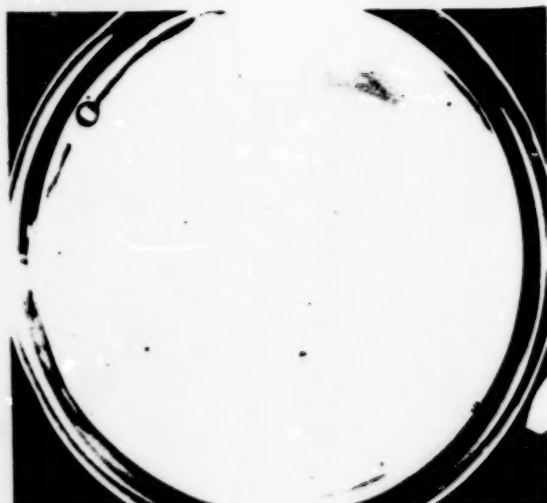


0 1cm

FIG. V.63 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

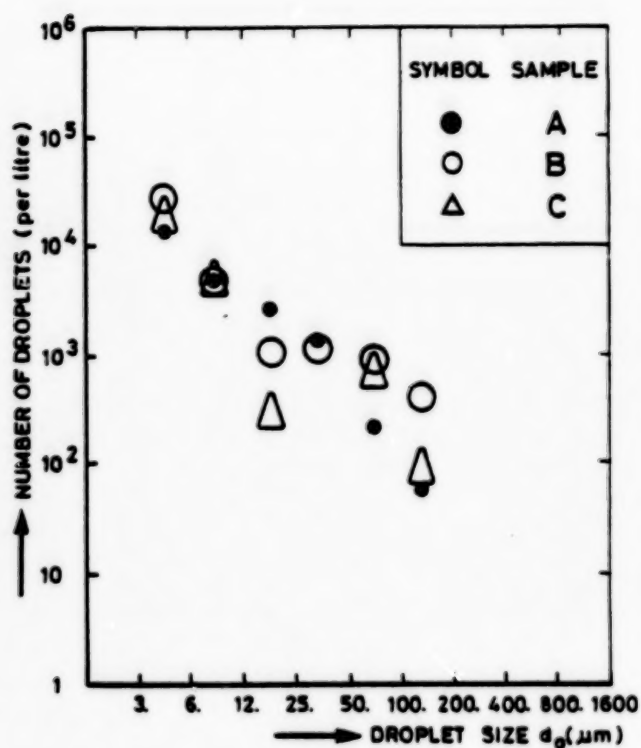


B



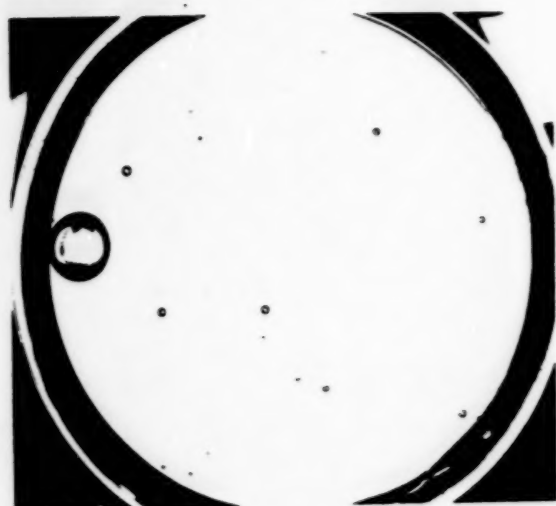
C

RUN S 15 PB₁₀
 SAMPLES 1 A,B,C
 WAVE 5 T_w= 1.0 s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43m
 SMALL-SCALE EXPERIMENT

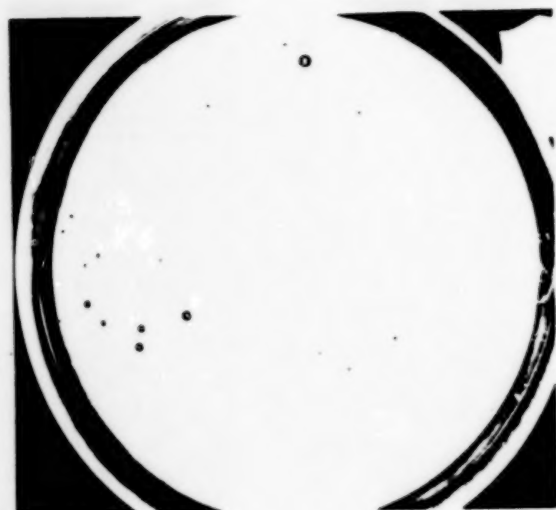


0 1cm

FIG. V. 64 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

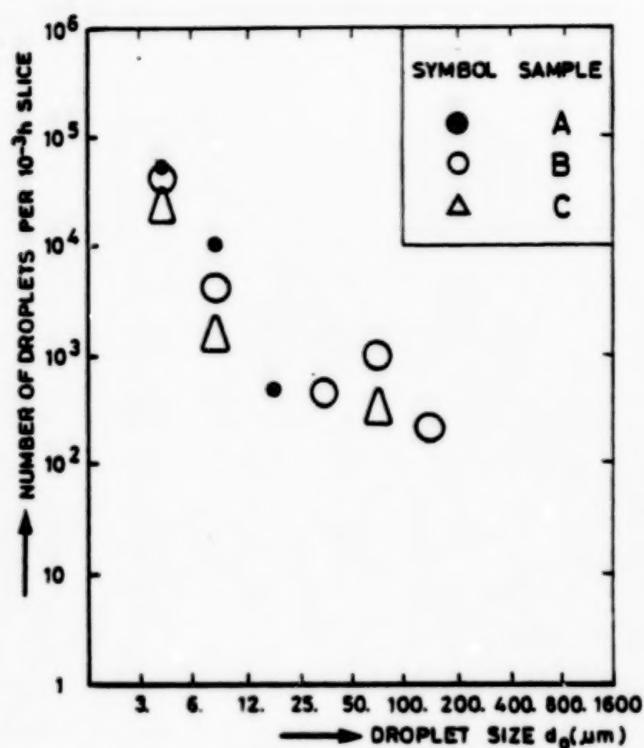


B



C

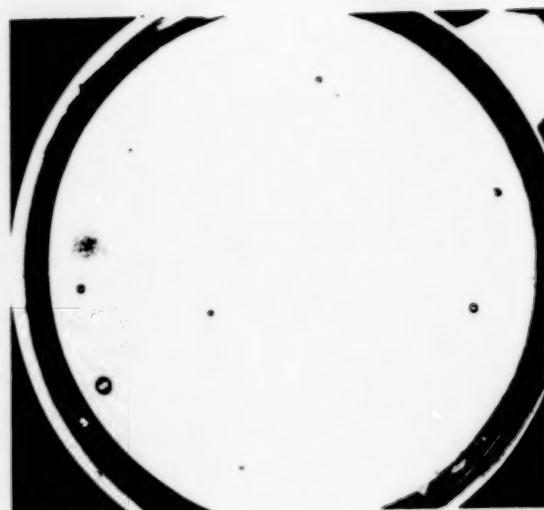
RUN S15 PB₁₀
 SAMPLES 2 A,B,C
 WAVE 5 T_w = 1.0 s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1cm

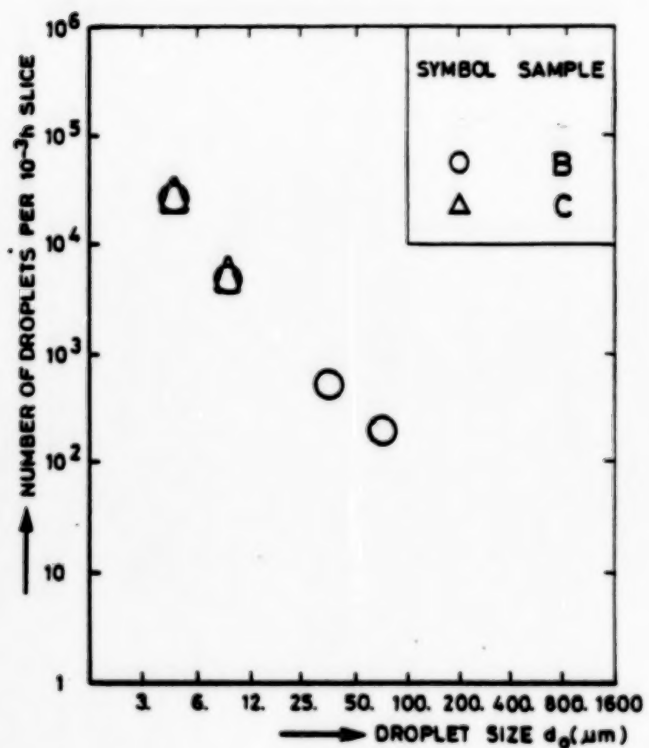
FIG. V.65 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.

RUN S 15 PB₁₀
 SAMPLES 3 B, C
 WAVE 5 T_w= 1.0 s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



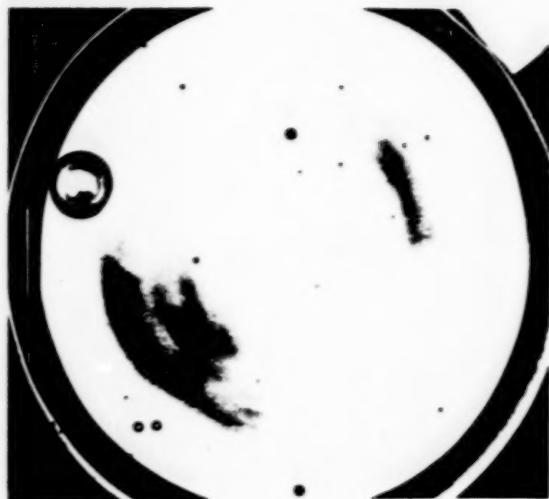
B

C

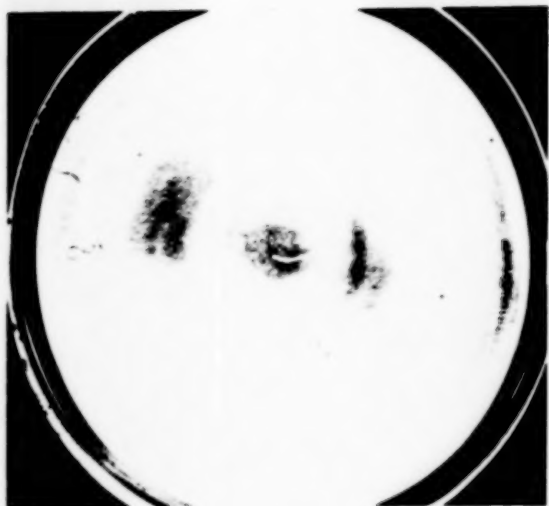


0 1cm

FIG. V.66 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

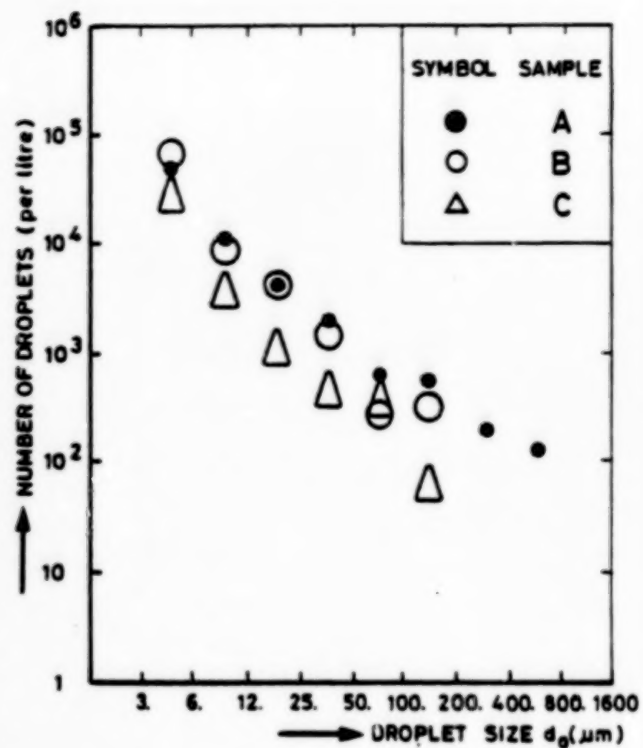


B



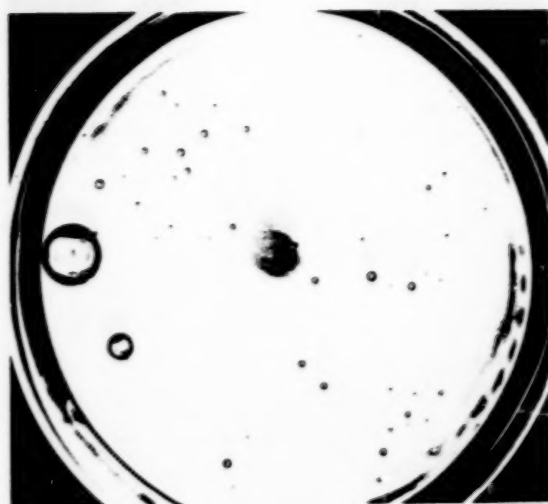
C

RUN S16 Eko
 SAMPLES 1 A,B,C
 WAVE 5 $T_w = 1.0$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1cm

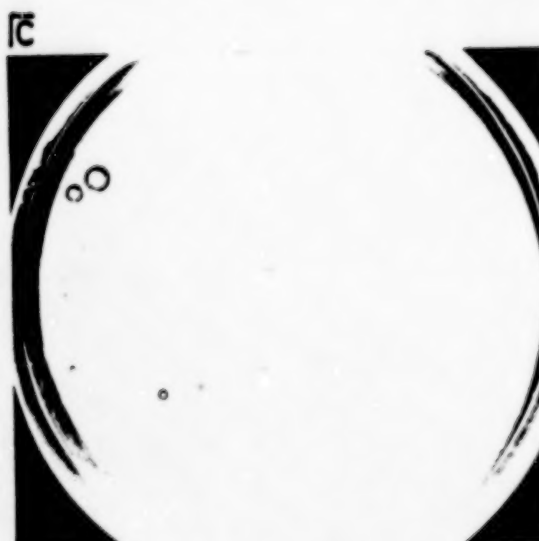
FIG. V. 67 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

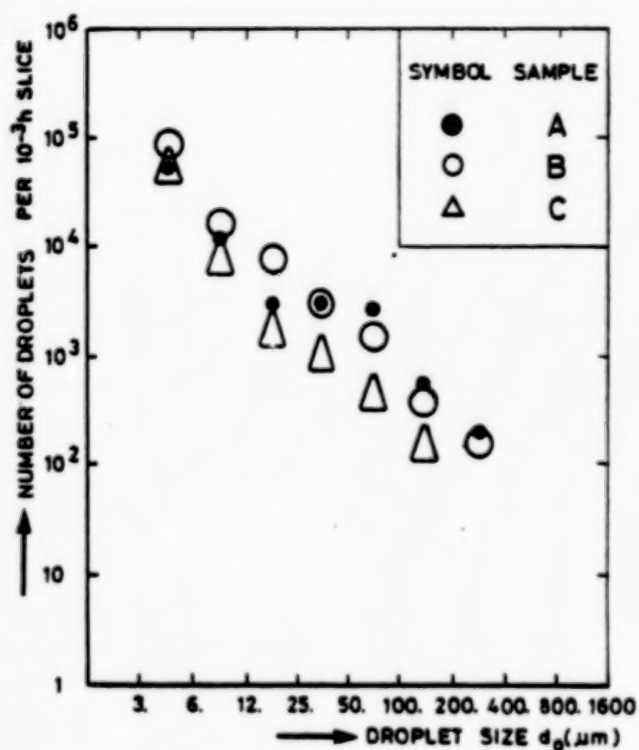


B



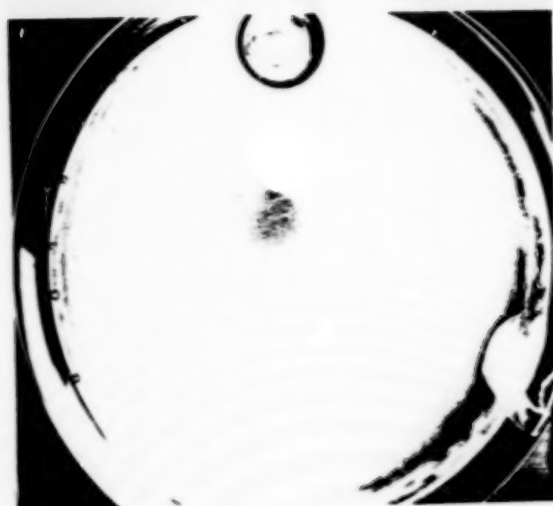
C

RUN S16 Eko
 SAMPLES 2 A, B, C
 WAVE 5 $T_w = 1.0$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

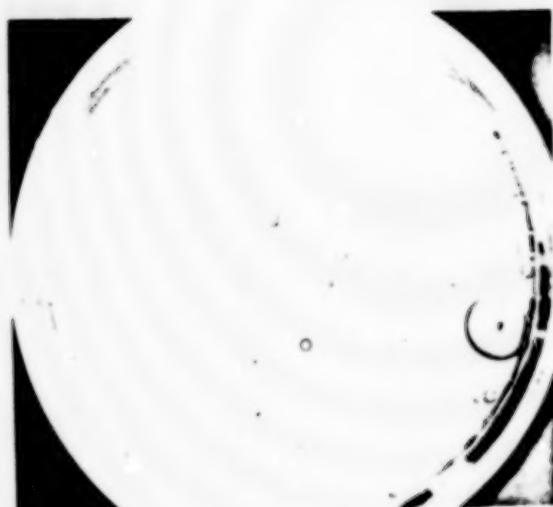


0 1 cm

FIG. V. 68 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A



B



C

RUN S16 Eko
 SAMPLES 3 A,B,C
 WAVE 5 $T_w = 1.0$ s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

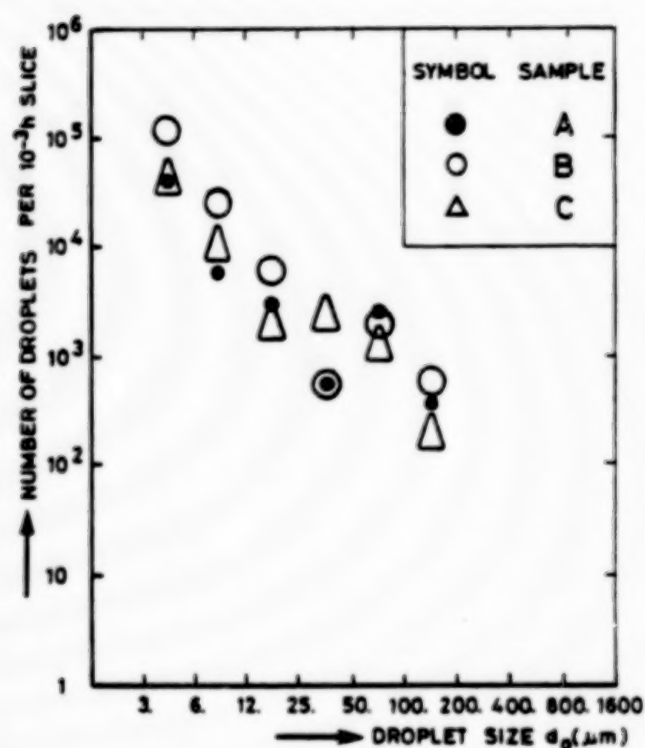
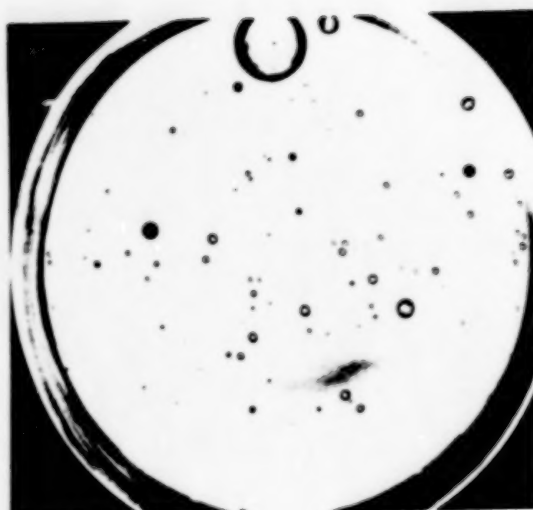


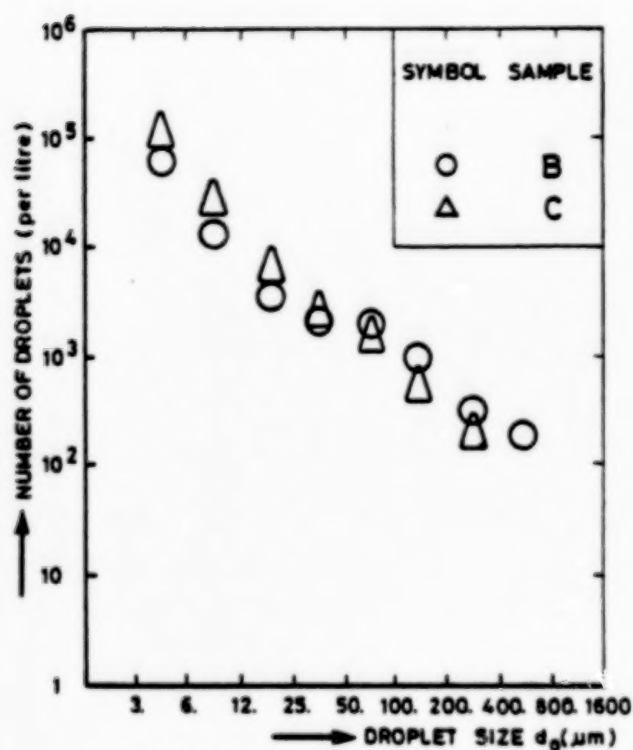
FIG. V. 69 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.

RUN S 17 PB_0
 SAMPLES 1 B, C
 WAVE 2 $T_W = 1.25$ s
 TEMPERATURE 2°C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43m
 SMALL-SCALE EXPERIMENT



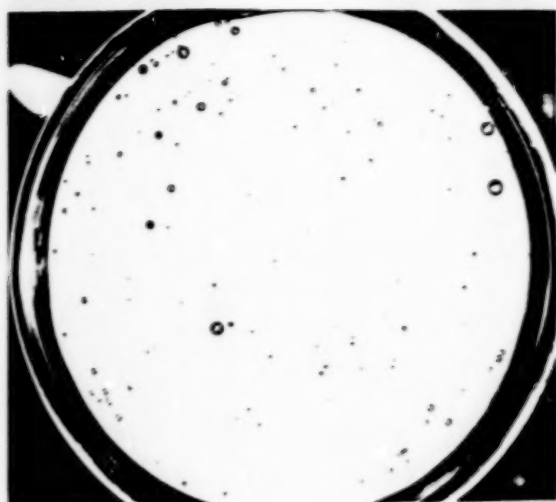
B

C

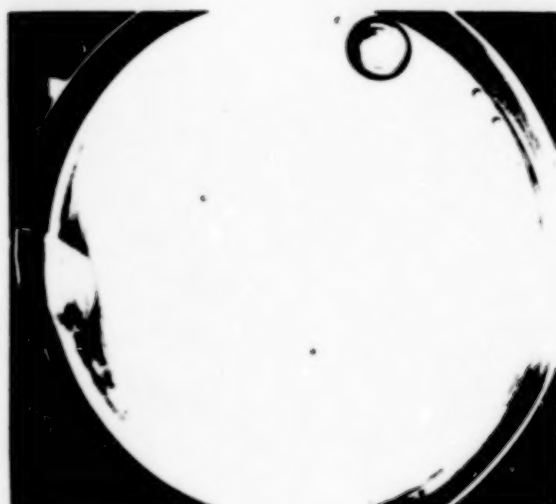


0 1cm

FIG. V. 70 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

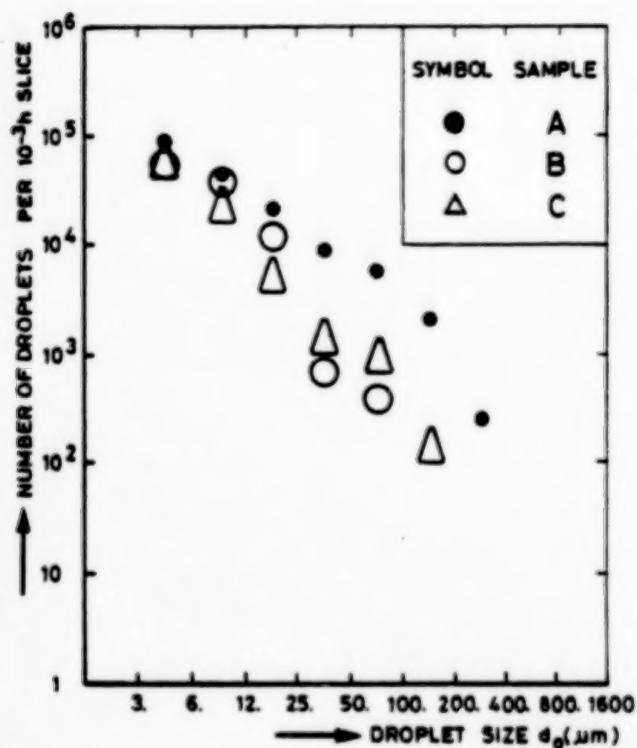


B



C

RUN S 17 PB_0
 SAMPLES 2 A,B,C
 WAVE 2 $T_w = 1.25$ s
 TEMPERATURE 2 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1cm

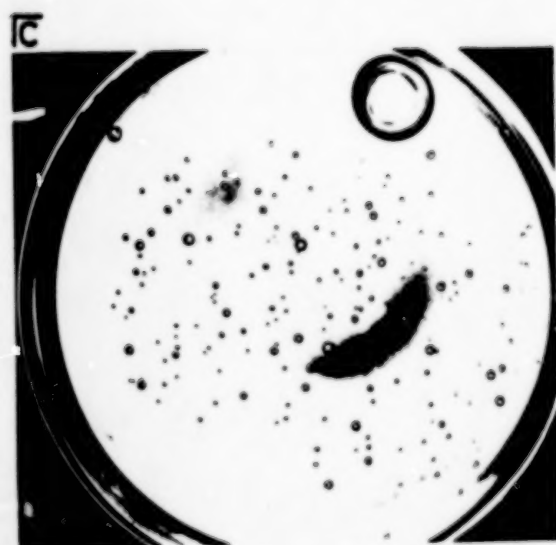
FIG. V. 71 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

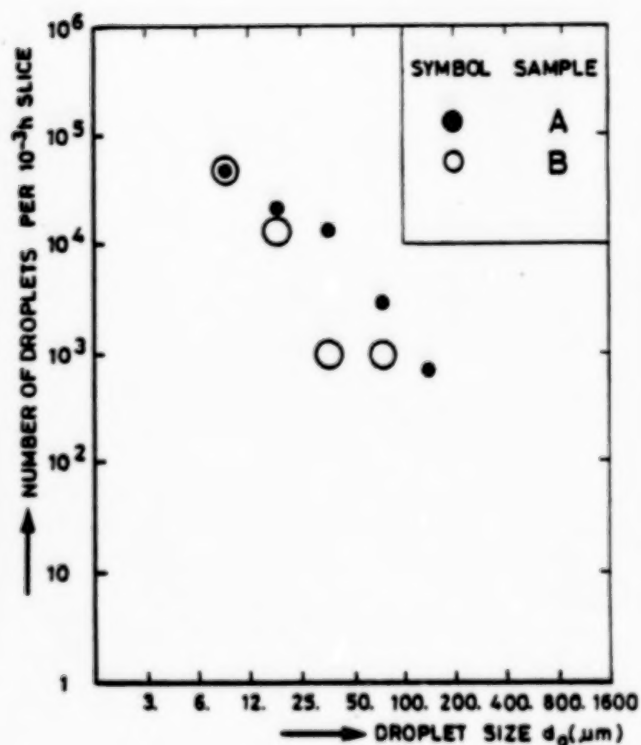


B



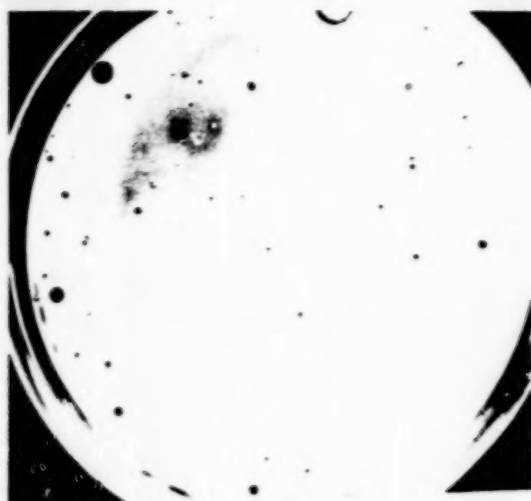
C

RUN S 17 PB_0
 SAMPLES 3 A, B
 WAVE 2 $T_w = 1.25$ s
 TEMPERATURE 2 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

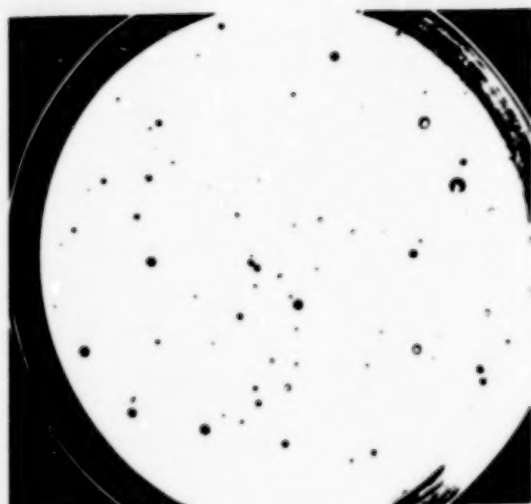


0 1 cm

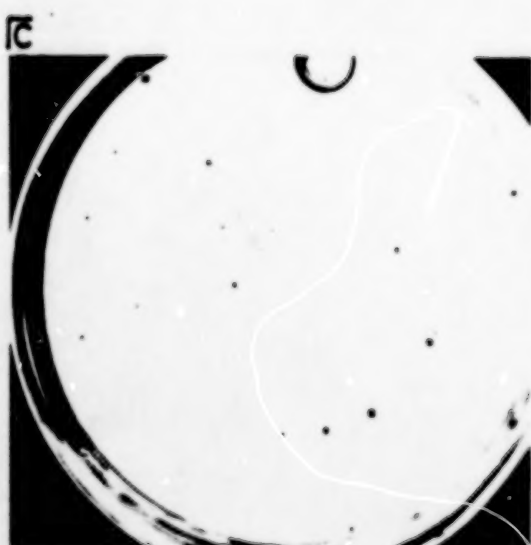
FIG. V. 72 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

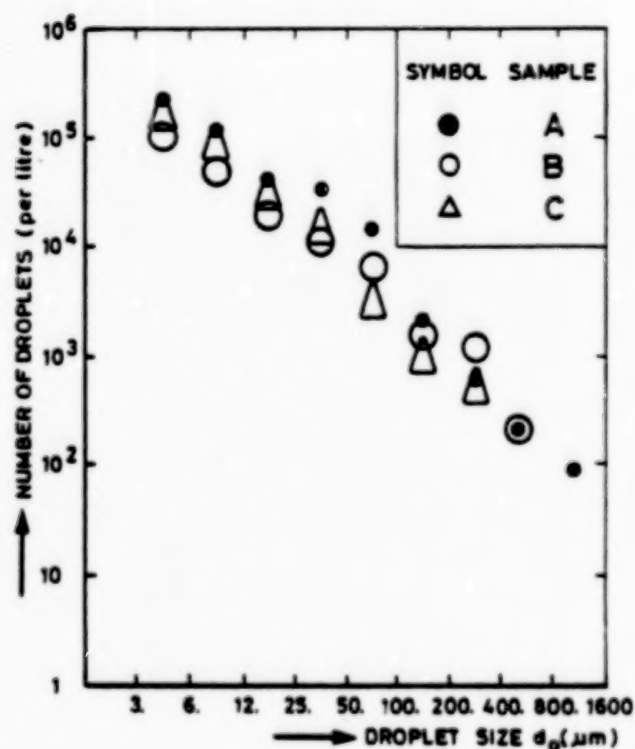


B



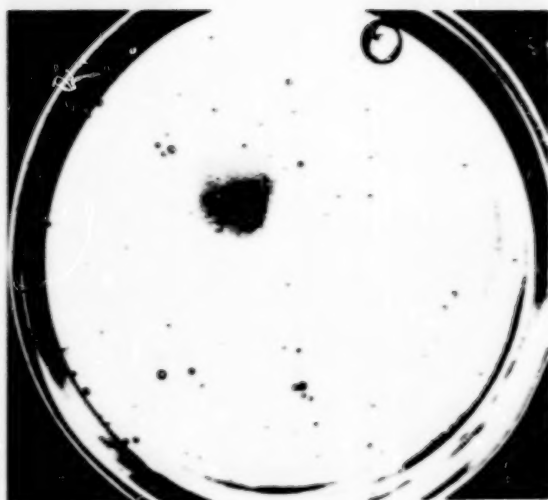
C

RUN S18 Eko
 SAMPLES 1 A,B,C
 WAVE 2 $T_w = 1.25$ s
 TEMPERATURE 2 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

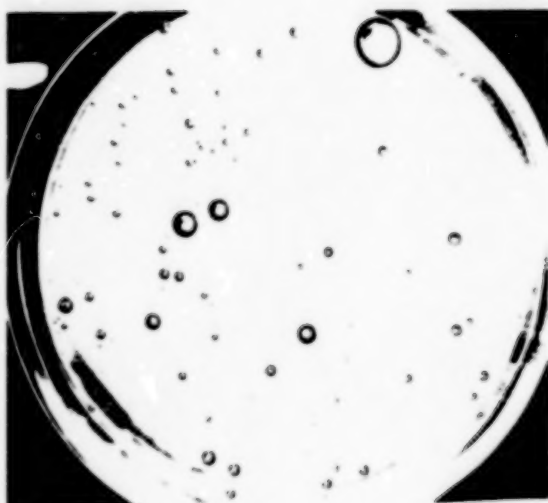


0 1 cm

FIG. V. 73 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

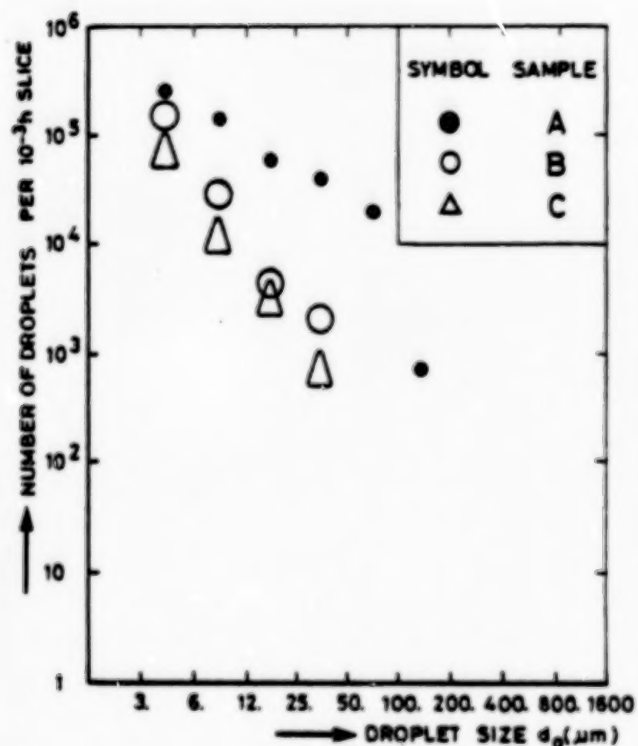


B



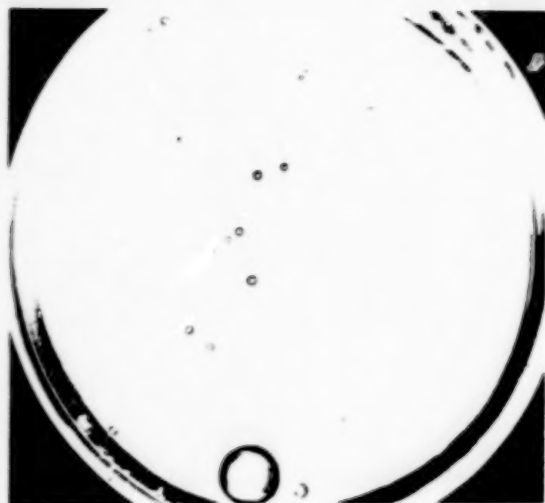
C

RUN S 18 Eko
 SAMPLES 2 A, B, C
 WAVE 2 $T_w = 1.25$ s
 TEMPERATURE 2 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1cm

FIG. V. 74 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

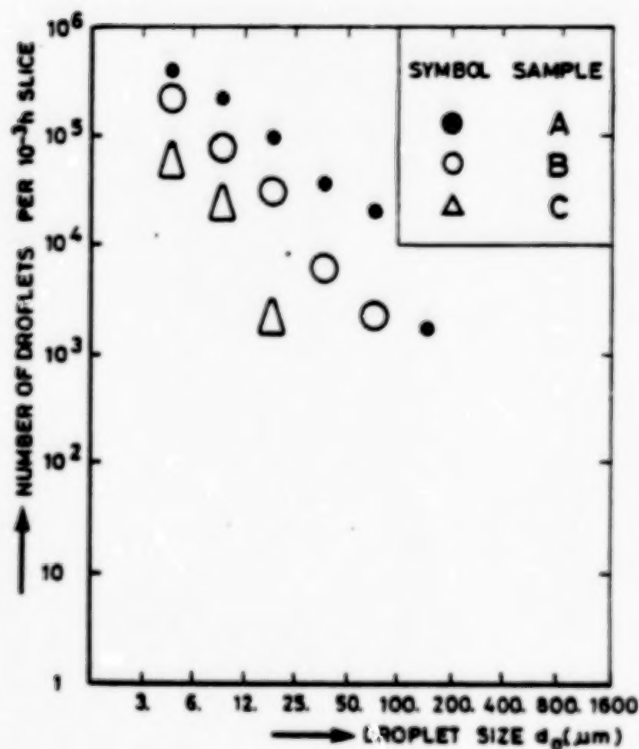


B



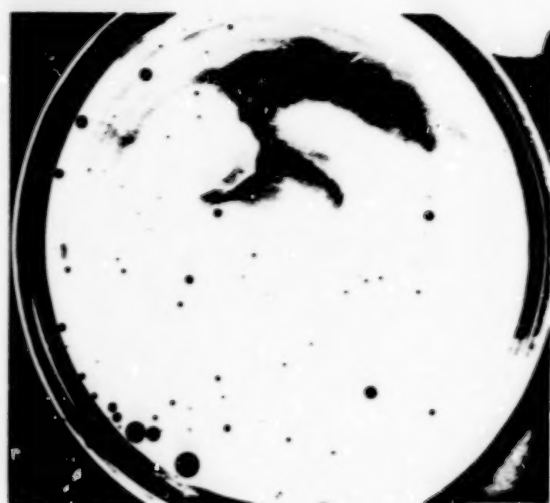
C

RUN S18 Eko
 SAMPLES 3 A, B, C
 WAVE 2 $T_w = 1.25$ s
 TEMPERATURE 2°C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

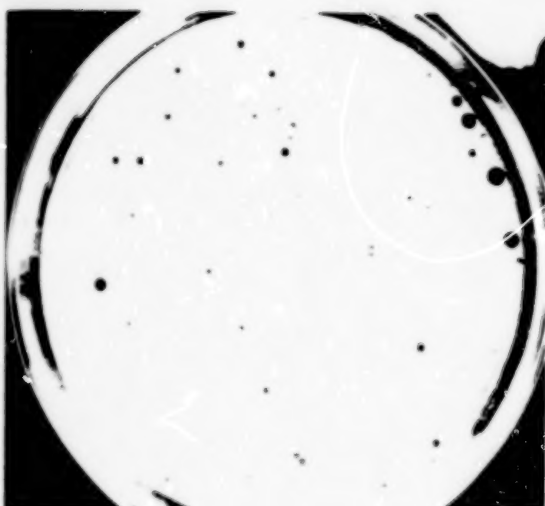


0 1cm

FIG. V. 75 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

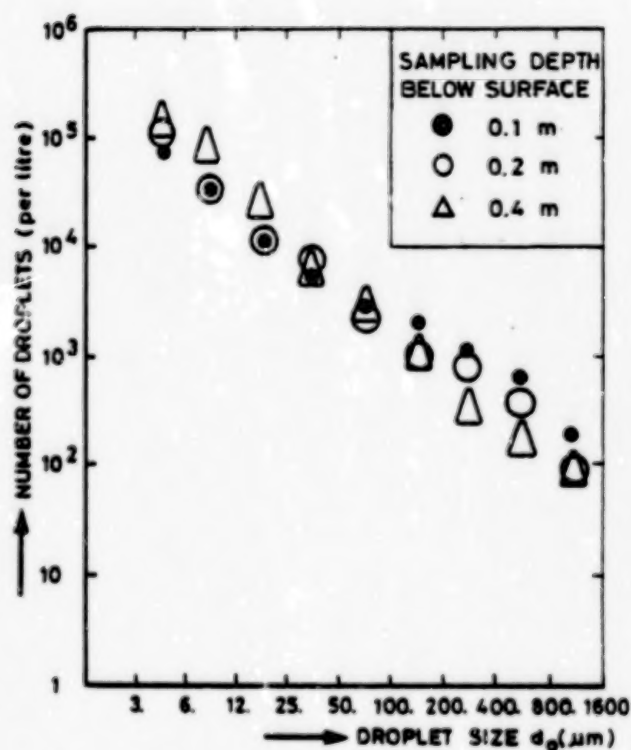


B



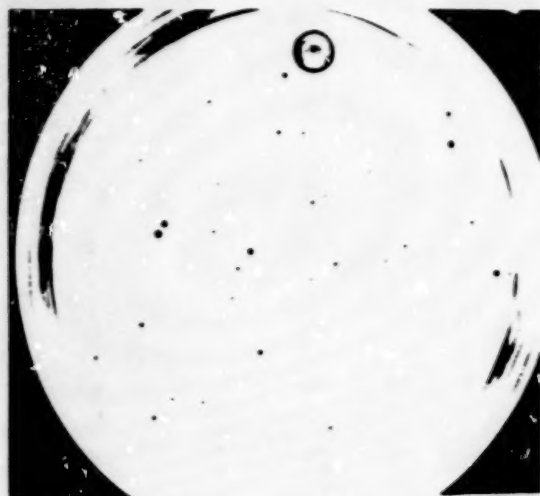
C

RUN S 19 PB₀
 SAMPLES 1 A,B,C
 WAVE 2 T_w = 1.25 s
 TEMPERATURE 8 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1 cm

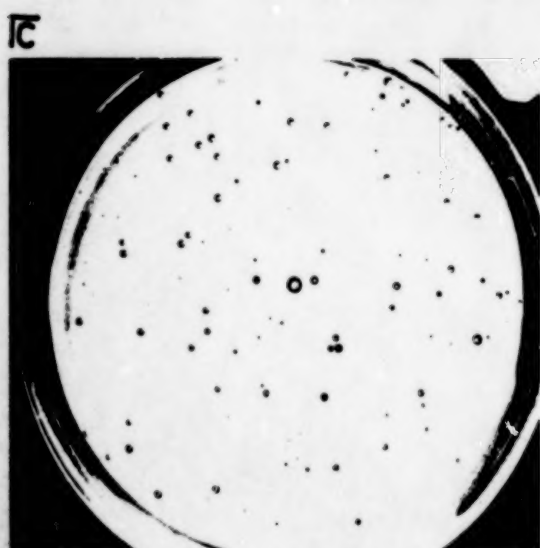
FIG. V. 76 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A



B



C

RUN S 19 PB₀
 SAMPLES 2 A, B, C
 WAVE 2. T_w = 1.25 s
 TEMPERATURE 8 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43m
 SMALL-SCALE EXPERIMENT

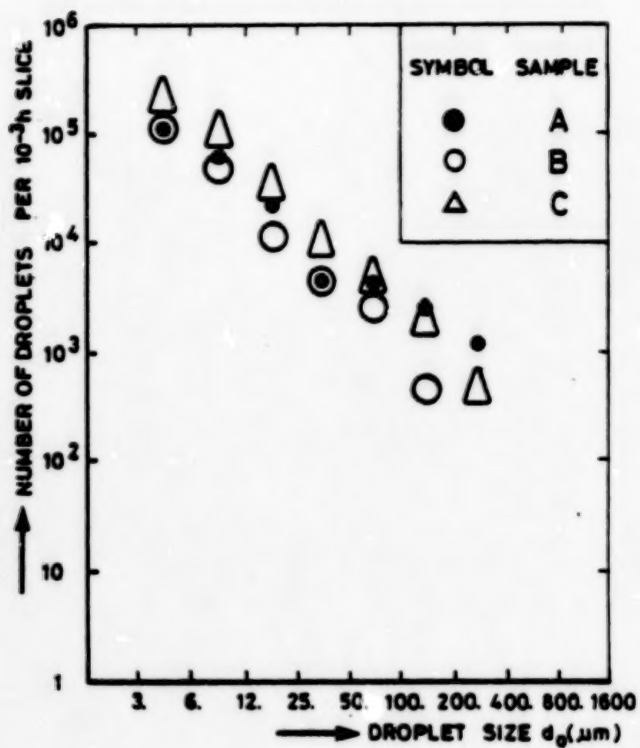
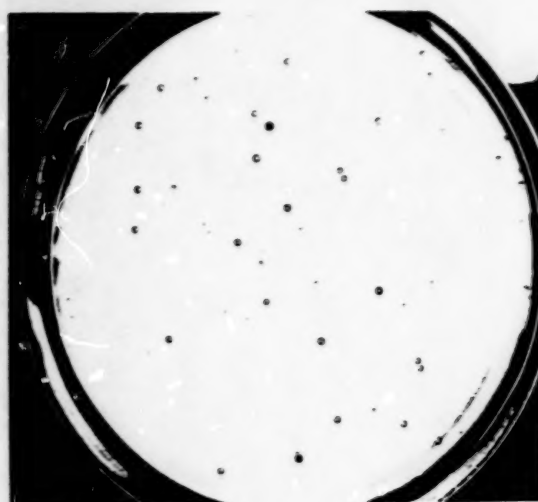


FIG. V. 77 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

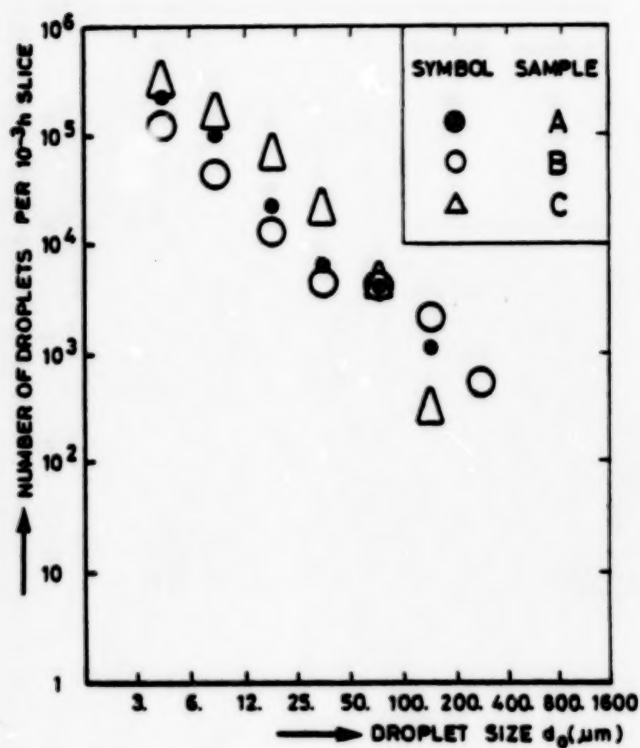


B



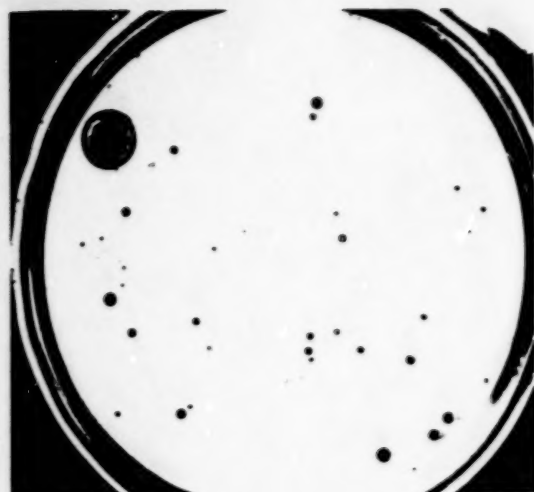
C

RUN S 19 PB₀
 SAMPLES 3 A, B, C
 WAVE 2 T_w = 1.25 s
 TEMPERATURE 8 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

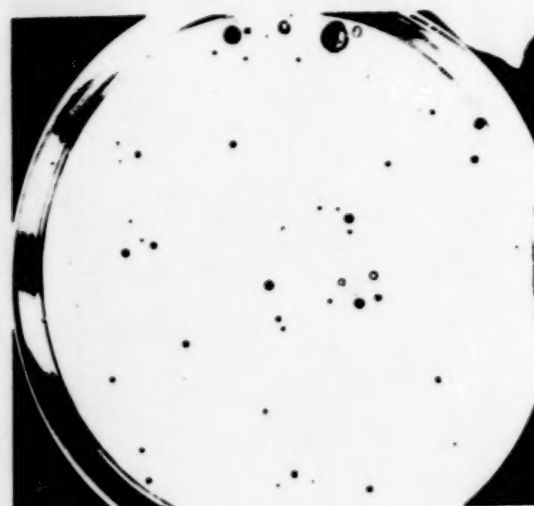


0 1 cm

FIG. V. 78 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

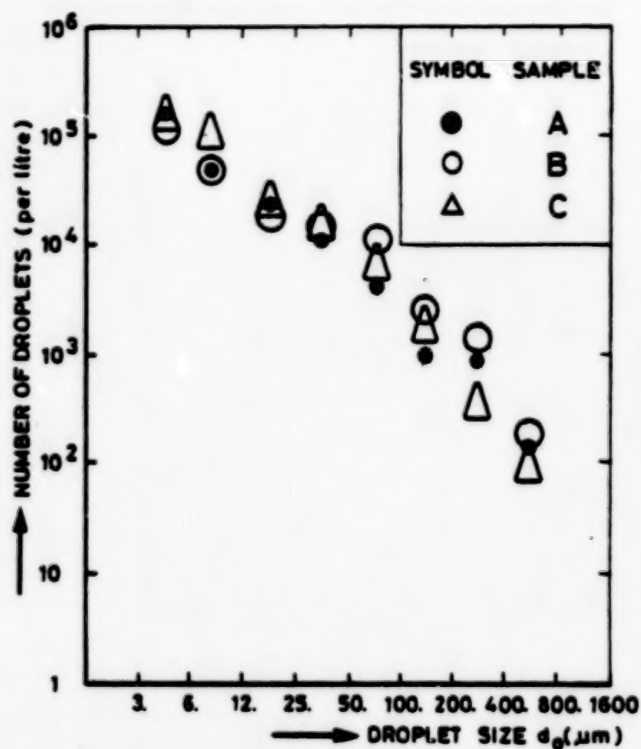


B



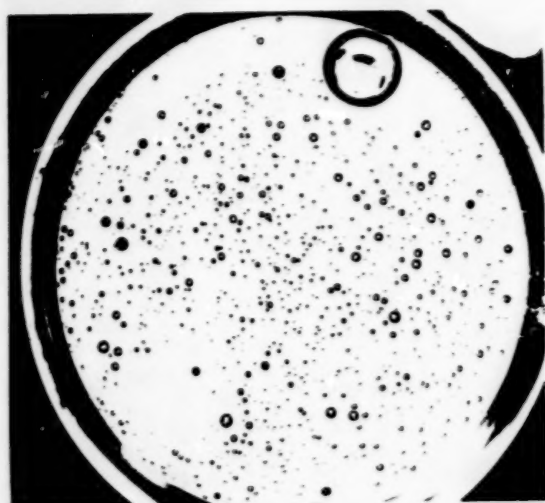
C

RUN S 20 Eko
 SAMPLES 1 A, B, C
 WAVE 2 $T_w = 1.25$ s
 TEMPERATURE 8 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

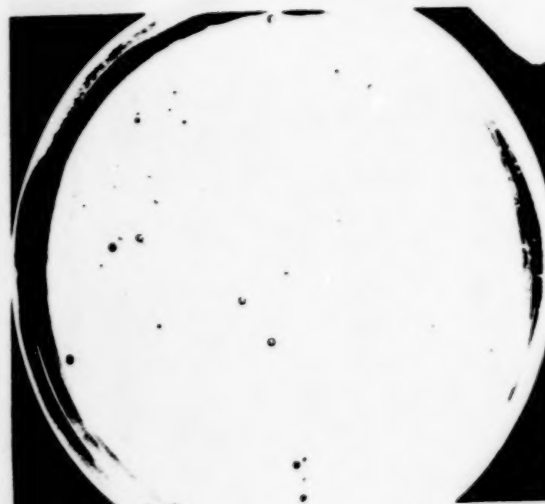


0 1cm

FIG. V.79 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

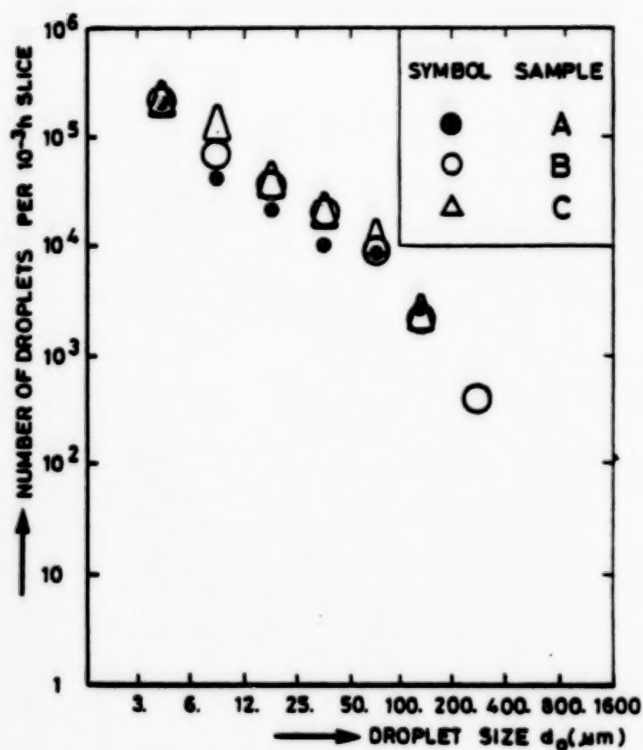


B



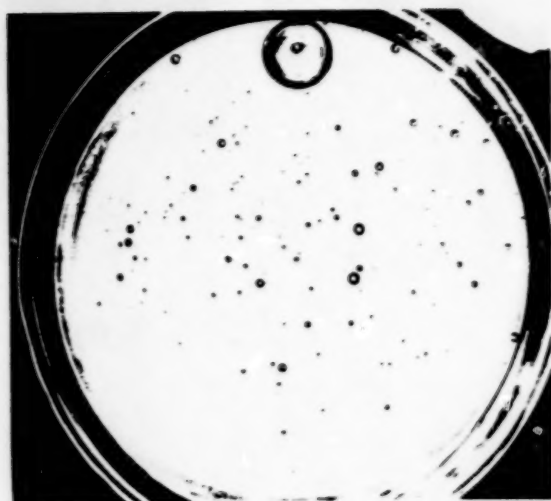
C

RUN S 20 Eko
 SAMPLES 2 A,B,C
 WAVE 2 $T_w = 1.25$ s
 TEMPERATURE 8 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43m
 SMALL-SCALE EXPERIMENT

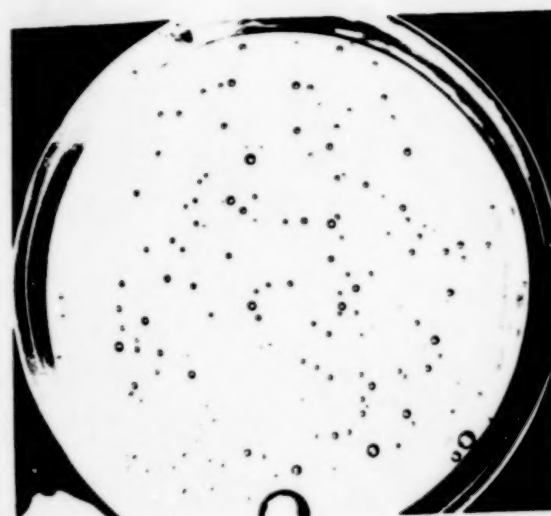


0 1cm

FIG. V. 80 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

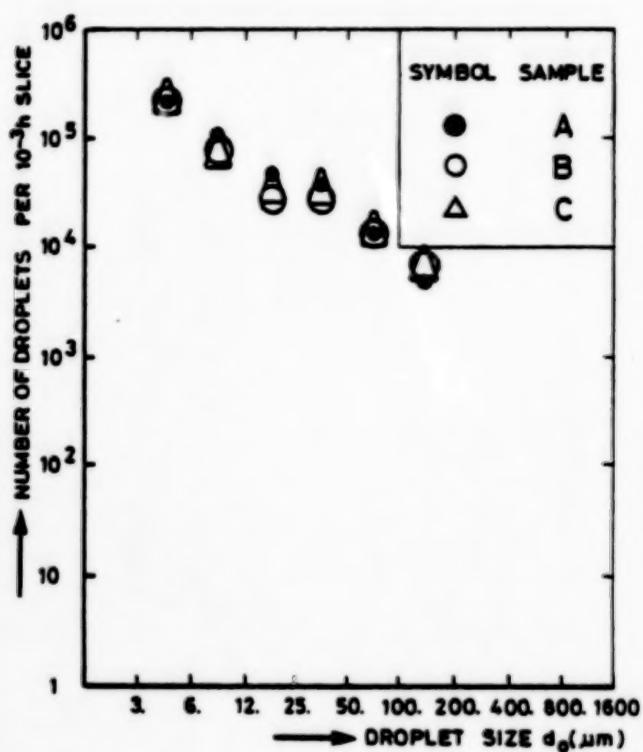


B



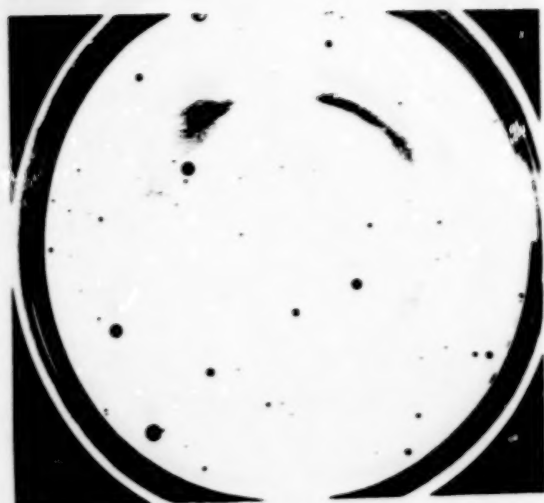
C

RUN S 20 Eko
 SAMPLES 3 A, B, C
 WAVE 2 $T_w = 1.25$ s
 TEMPERATURE 8 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

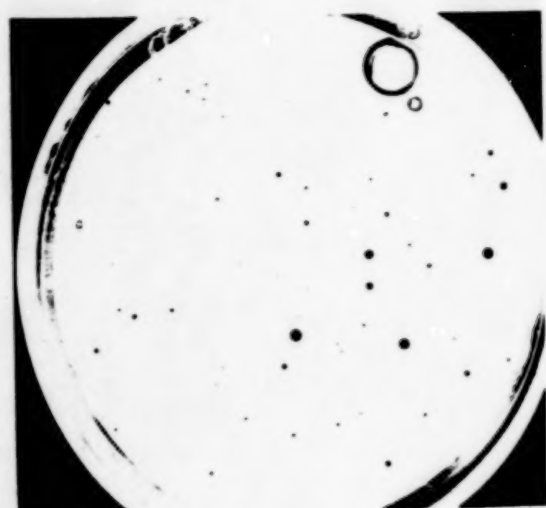


0 1cm

FIG. V. 81 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

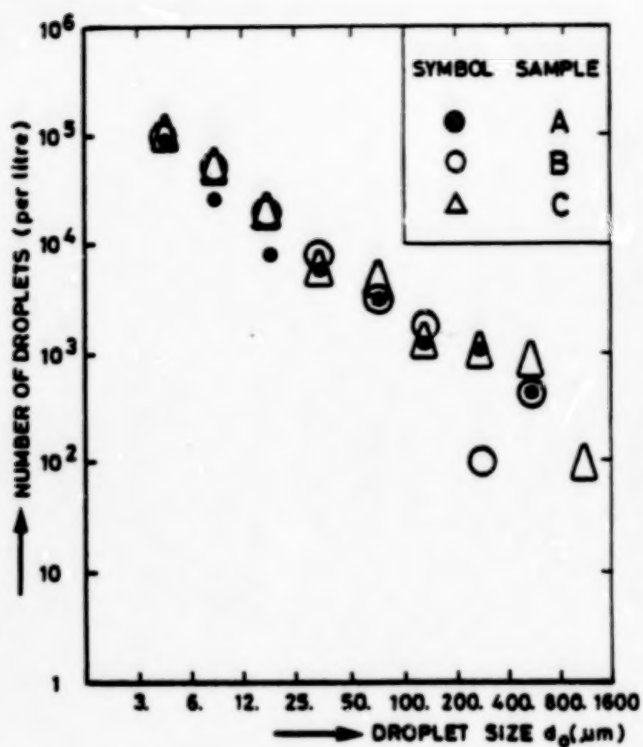


B



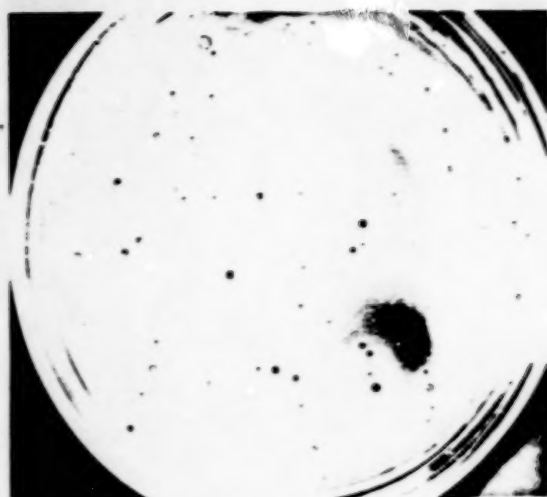
C

RUN S21 PB₀
 SAMPLES 1 A, B, C
 WAVE 2 T_w = 1.25 s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

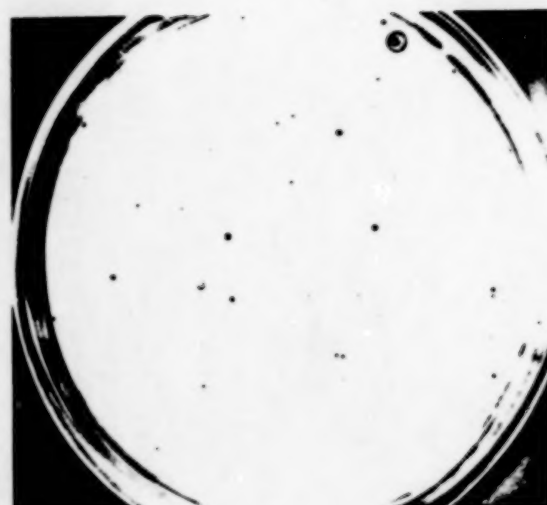


0 1 cm

FIG. V. 82 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

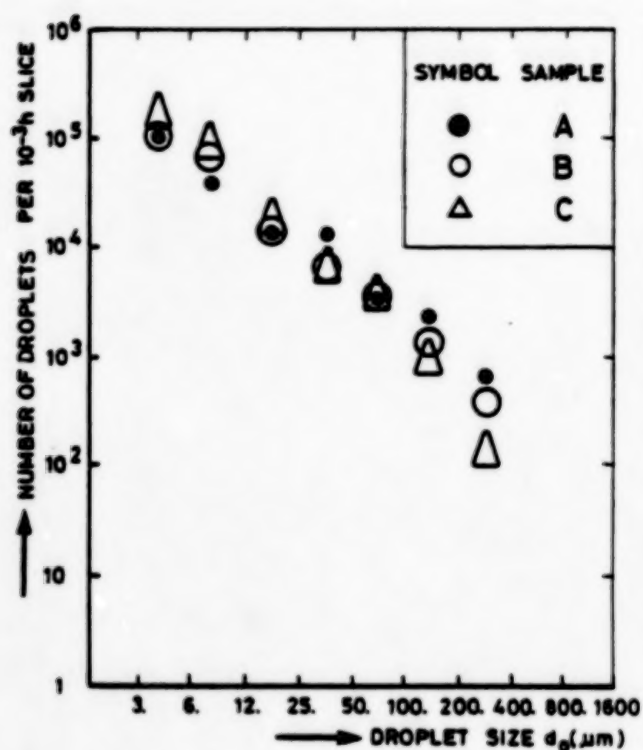


B



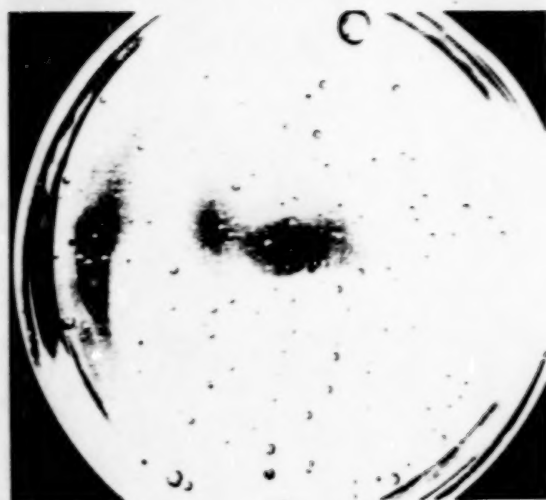
C

RUN S 21 PB₀
 SAMPLES 2 A,B,C
 WAVE 2 T_w = 1.25 s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT

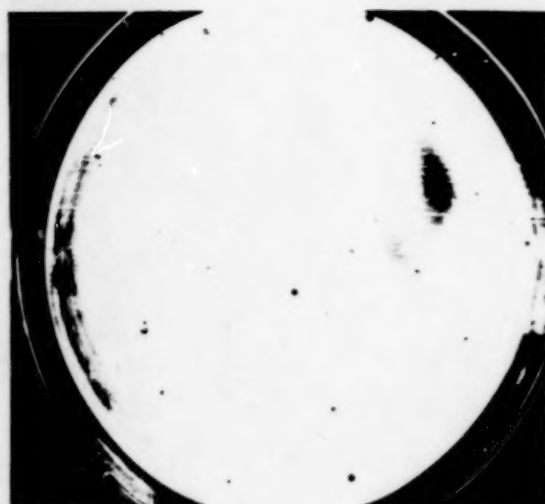


0 1cm

FIG. V. 83 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

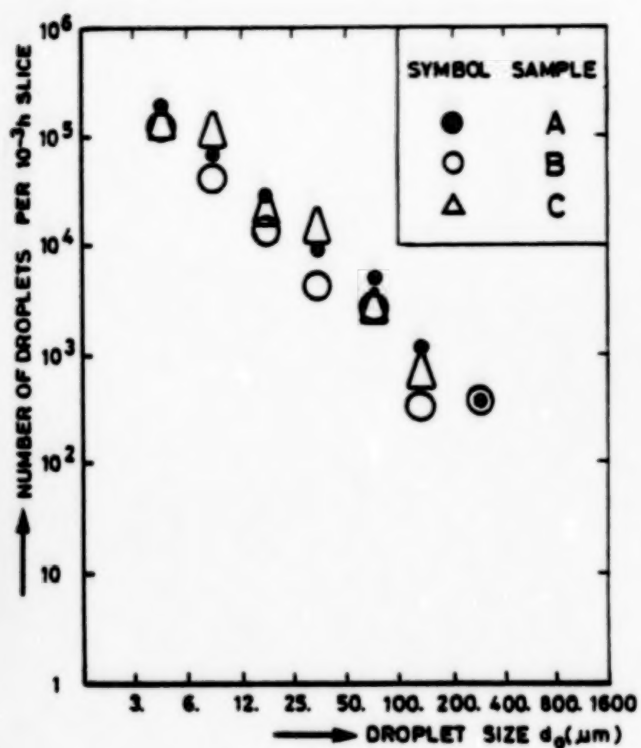


B



C

RUN S 21 PB₀
 SAMPLES 3 A, B, C
 WAVE 2 T_w = 1.25 s
 TEMPERATURE 15 °C
 OIL LAYER 0.6 mm
 WATERDEPTH 0.43 m
 SMALL-SCALE EXPERIMENT



0 1cm

FIG. V. 84 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.

Table V.5 Oil droplet intrusion depths, z_i , due to breaking waves

parameter	wave 2	wave 3	wave 5	wave 7
H_b	0.23	0.24	0.15	0.10
h_{bore}	0.12	0.12	0.08	0.04
z_i	0.40	0.325	0.20	0.15
z_i/H_b	1.74	1.35	1.33	1.50
z_i/h_{bore}	3.33	2.70	2.50	3.75

tive to a size range interval around the droplet size d_0 where the interval is proportional to d_0 . In the graphs, the intervals $0.7 d_0$ to $1.4 d_0$ centered around d_0 were chosen (i.e., centered around d_0 on a logarithmic scale).

V.7 Measurements of Oil Intrusion

The intrusion depth of oil droplets from a surface slick into the water column due to breaking waves was observed in the Oil Flume by taking photographs. Figure V.6 shows the initial intrusion of droplets in some tenths of a second after the passage of the breaking wave (wave 1 in Figure V.6). The initial intrusion is due to the mixing in the bore of the breaking wave, while the intrusion depth is of the same order as the height of the bore. However, the intrusion proceeds by the (decaying) turbulence in the upper water layer in the successive tens of seconds after the wave passage. This is shown by the dye experiment with wave 2 in Figure V.7. The final intrusion depth z_1 , due to the bore turbulence, is the most interesting parameter as regards the dispersion of oil.

z_1 is defined as the depth of the almost homogeneous dye concentration, averaged over the length of the breaking wave. z_1 for wave 2, wave 3, wave 5 and wave 7 was measured visually by dye experiments. Photographs of experiments with wave 2, wave 5 and wave 7 are shown in Figure V.26, V.27 and V.28 respectively. The values of z_1 are given in Table V.5, together with the wave heights of the breaking waves H_b , the bore heights h_{bore} and the ratios z_1/H_b and z_1/h_{bore} .

V.8 Discussion and Results

The two series of experiments, with the laser-beam particle sizer and with microscopic observation of the droplet size distributions, are considered in this Section. Experimental data consist of the droplet size distributions, the oil concentration measurements obtained by infra-red spectro-

scopy, and the dye observations on the extension of the (oil droplet) clouds due to breaking waves. The discussion concludes with in relationships regarding the droplet size distribution of dispersed oil, the intrusion depth of oil droplets, and the entrainment of surface oil by a breaking wave.

The following discussion is restricted to the experiments with single breaking waves. Some experiments were conducted with regular repeated breaking waves (see Table V.2) with intervals of 15, 30 or 60 seconds, but it was concluded that the droplet distribution and concentration measurements in these experiments could never be related to clear external parameters as oil layer thickness, oil viscosity etcetera. Many conditions changed rapidly in the course of the experiments due to the following features:

- a) the surface oil slick was originally restricted to a homogeneous film in the two metres long breaking wave and measuring section but spread soon over a wide flume section broken up into patches irregular in size and thickness,
- b) rapid emulsification did occur due to the mechanical action of the breaking waves, especially with Prudhoe Bay oil. Consequently, the oil viscosity increased rapidly during an experiment,
- c) Many oil droplets moved out of the measuring section and spread over the entire flume due to (uncontrolled) currents induced by the wave generator. Consequently, experiments with repeated breaking waves were not conducted in the second series of experiments with the oil droplet samplers (see Table V.3).

V.8.1 Droplet size distribution

The most important result obtained from the $N(d_o)$ versus d_o graphs in the Figures V.31 to V.84 was the linear relationship between $\log N(d_o)$ and $\log d_o$. The relationship appeared valid for all measured size classes except the classes with the largest droplet sizes. Moreover, the relationship was valid for all experiments independent of the oil type, layer thickness, temperature and oil weathering state, and in addition the slopes of the

curves were highly invariable. The graphs lead to the equation:

$$N(d_o) \sim d_o^{-1.3} \quad (5.16)$$

with $N(d_o)$ = number of droplets in the $0.7 d_o$ to $1.4 d_o$ droplet size interval.

It is postulated that, in the first instance immediately after the breaking event, Equation (5.16) is valid for all droplet size classes from infinitely small to infinitely large. However, big droplets and oil lumps resurface very quickly after the passage of the breaking wave, leading to a droplet size distribution in the water mass that deviates from Equation (5.16) as far as the large droplet size classes are concerned. This deviation eventually affects smaller size classes if no residual turbulence is present to keep these droplets in suspension.

Equation (5.16) leads to the following equation as regards the relative volume of oil in the size classes:

$$V_t(d_o) = 1.45 V(d_o) \quad (5.17)$$

with $V(d_o)$ = volume of oil in the droplet size interval $0.7 d_o$ to $1.4 d_o$,
 $V_t(d_o)$ = total volume of oil droplets smaller than $1.4 d_o$ (down to infinitely small).

Equation (5.16) was supported by droplet size measurements down to the droplet size class 3 to $6 \mu\text{m}$. It is not known how far Equation (5.16) can be extrapolated to smaller size classes. Equation (5.17) indicates that the oil volume of droplets smaller than $3 \mu\text{m}$ is very small relative to larger size classes, even if extrapolation is possible down to infinitely small droplets.

V.8.2 Intrusion depth

The measurements of the wave height H_b of the breaking wave, the bore height h_{bore} and the intrusion depth z_1 due to the breaking wave lead to

linear relationship between H_b and z_1 , and h_{bore} and z_1 . (See Table V.5). The averaged values of z_1/H_b and z_1/h_{bore} for the four different waves result in:

$$z_1 = 1.5 (\pm 0.25) H_b \quad (5.18a)$$

and

$$z_1 = 3.1 (\pm 0.7) h_{bore} \quad (5.18b)$$

The numbers in between brackets indicate the spread of the empirical coefficients.

V.8.3 Oil entrainment

As regards the oil dispersion experiments in the flume, the entrainment Q (kg/m^2) is defined as the dispersed oil mass in the water column due to the break-up of a unit area of a surface oil film by a (single) breaking wave. Q depends strongly on t_m , where t_m is the time since the passage ($t_m = 0$) of the breaking wave. In principle, $Q(t_m=0)$ equals the surface slick mass per m^2 because all surface oil is submerged by the breaking wave. However, the oil lumps and big oil droplets resurface almost immediately after the breaking event and subsequently, droplets with even smaller sizes resurface if the ambient turbulence is not capable to keep the droplets in suspension.

Empirical descriptions of the entrainment Q from oil concentration measurements in the water column are hampered by the droplet resurfacing process that causes time-dependent oil concentrations as well as concentrations dependent on the distance to the surface, z , even if the concentration was homogeneous at $t_m = 0$ within the depth of initial intrusion, z_1 . Therefore, the following description of the entrainment Q and droplet size distribution $d_o(f)$ is pursued:

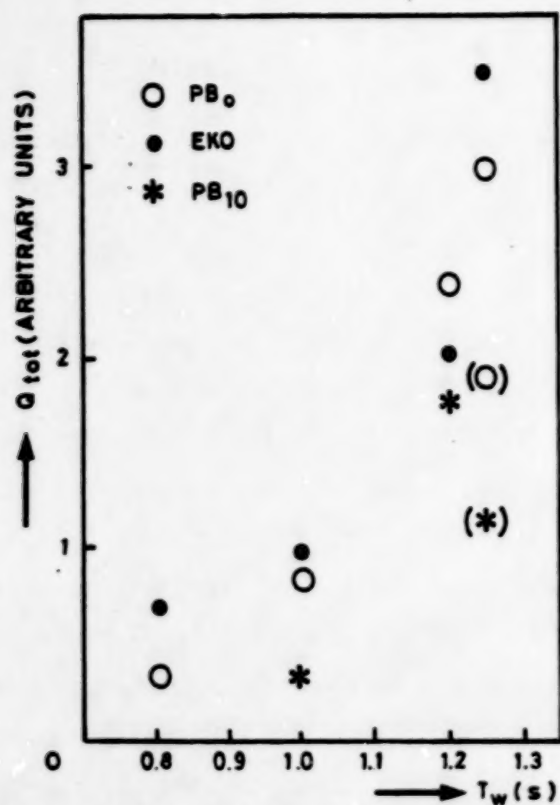
- a) The $N(d_o) - d_o$ graphs (see Figures V.31 to V.84) indicate a vertically homogeneous concentration in each size class of (small) droplets that is not (yet) distorted by resurfacing. Homogeneity exists over the depth of intrusion, z_1 (=definition of z_1).

- b) The relative numbers of droplets in the various size classes are given by Equation (5.16): $N(d_o) \sim d_o^{-1.3}$. In the first instance, the droplet sizes range from infinitely small to infinitely large.
- c) Absolute values of $N(d_o)$ are derived from the oil droplet samples for one or more size classes of small droplets that fulfill the homogeneity described in a.
- d) All measured droplet size distributions $d_o(f)$ continue, as regards the small droplets, down to at least $d_{min} = 3 \mu m$. Continuation until $d_{min} = 0$ is supposed with relative size class concentrations according to Equation (5.16). (The volume of oil with $d_o < 3 \mu m$ is generally negligible as compared with the total volume of dispersed oil.)
- e) The maximum droplet size d_{max} at a given time t_m and at a given depth z_1 might be derived from measurements (oil droplet samples) or from calculations of the vertical diffusion in the oil droplet cloud. (Parameters in the calculation are the vertical diffusion coefficient, c_z , the terminal velocity of the oil droplet considered, W , and the vertical coordinate, z_1). All droplets in a smaller size class than d_{max} fulfill the conditions in a. and b. at the considered time t_m and at depths z with $z \leq z_1$.

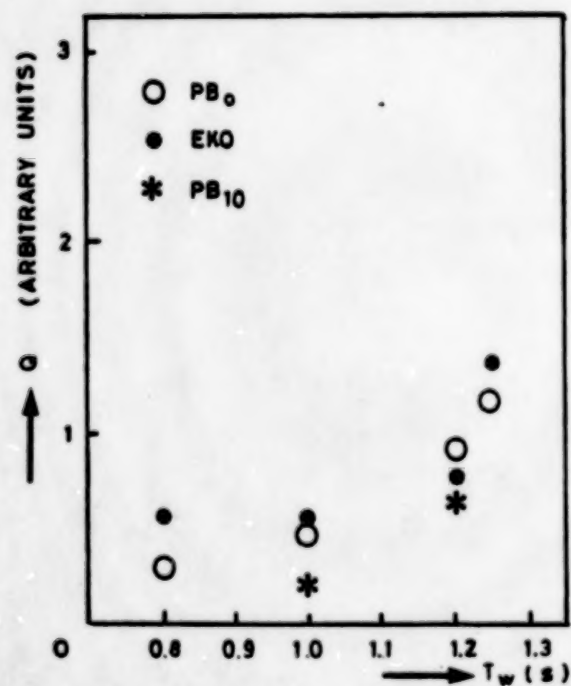
Or to put it in other words, the entrainment of oil by a breaking wave is described by:

- a) intrusion depth z_1
- b) relative $d_o(f)$ distribution with $N(d_o) \sim d_o^{-1.3}$
- c) homogeneous $N(d_o)$ distribution over $z \leq z'$
 [especially: $N(d_o)$ homogeneity within z_1 for $d_o < d_{max}(z', t_m)$
 for $d_o \leq d_{max}(z_1)$]
- d) absolute value of $N(d_o)$ for at least one size class
- e) empirical and/or calculated data on $d_{max}(z, t_m)$
- f) empirical and/or calculated data on $N(d_o)(z, t_m)$ for
 $d_o \geq d_{max}(z', t_m)$ and $z \leq z'$
 where z and z' are vertical coordinates with $0 \leq z, z' \leq z_1$.

Empirical results for oil entrainment dependence on type of breaking wave, type of oil and weathering state, temperature and surface layer thickness

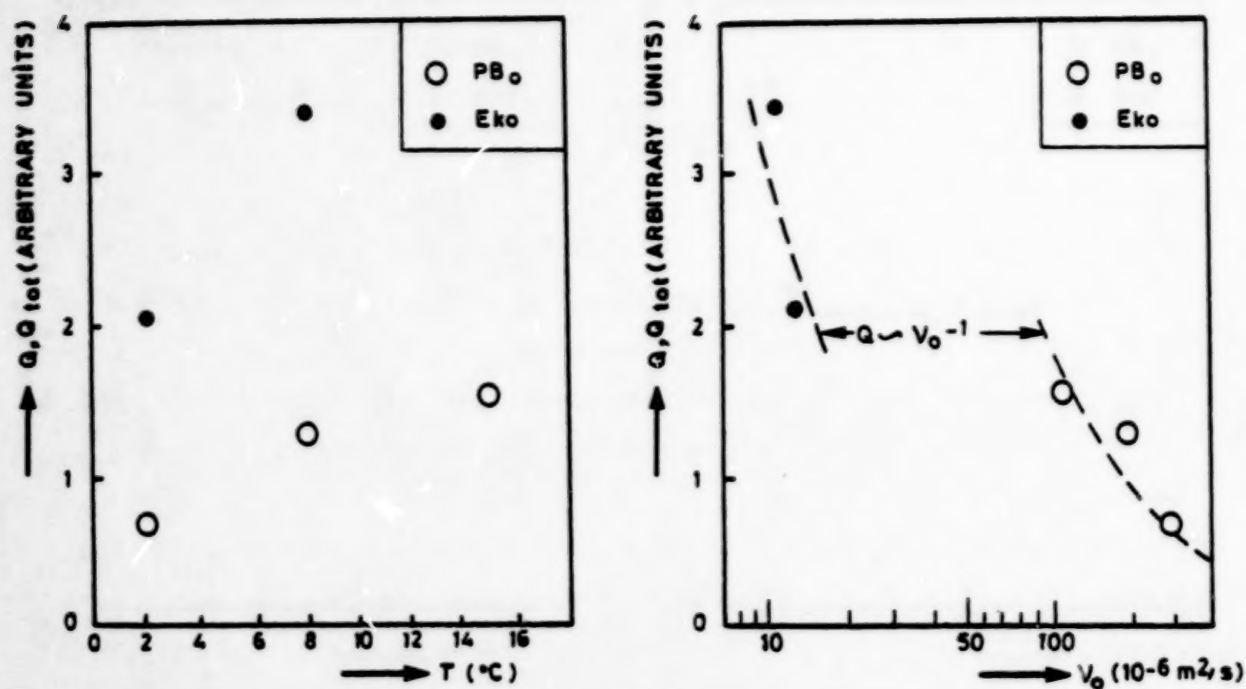


a) total oil entrainment in breaking wave

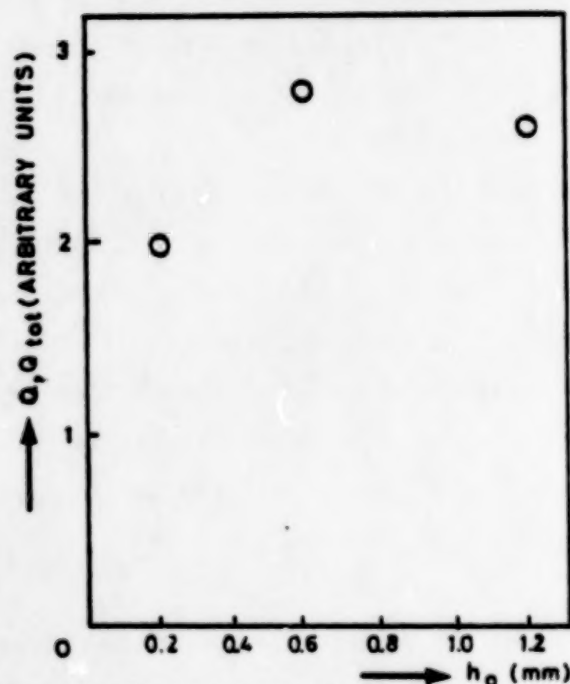


b) oil entrainment per unit area in breaking wave

FIGURE V.85 Oil entrainment due to different breaking waves



a) Q versus temperature T and viscosity v_0 (wave 2)



b) Q versus layer thickness h_0 (wave 3, PB_0)

FIGURE V. 86 Oil entrainment with different temperatures and surface layer thicknesses

are given in Figure V.85 and V.86. The data were derived from curve-fitting of the $N(d_o) - d_o$ graphs of the specific experiment with the general curve slope given by Equation (5.16). Curve-fitting took place for droplet sizes smaller than 200 μm . These droplets were in any case in suspension in the flume during sampling. The $N(d_o) - d_o$ graphs of the samples 2A, 2B, 2C and 3A, 3B, 3C were used for this purpose. These samples deal with the oil entrainment $Q_{\text{tot}}(\text{kg/m})$ due to the entire breaking wave per unit width. (The samples 1A, 1B, 1C deal, more or less, with the oil entrainment $Q (\text{kg/m}^2)$ per unit area of the breaking wave). The entrainment parameters are given on a relative scale in the figures.

Figure V.85 shows the oil entrainment for the waves 2, 3, 5 and 7, with wave periods $T_w = 1.25, 1.2, 1.0$ and 0.8 s respectively. The entrainment increased with increasing wave energy. The experiments were performed with PB_o , PB_{10} and Ekofisk oil. Apparently, the entrainment Q was larger for Ekofisk and smaller for PB_{10} , relative to the entrainment for PB_o . Figure V.85a indicates the oil entrainment per breaking wave Q_{tot} , for the entrained oil integrated over the entire length of wave breaking. The entrainment per unit length of wave breaking is shown in Figure V.85b by the parameter Q with $Q = Q_{\text{tot}}/l_b$. (l_b = bore covered length).

Oil entrainment versus temperature (T) is shown in Figure V.86a. The experiments were performed with wave 2 and temperatures $T = 2^\circ\text{C}, 8^\circ\text{C}$ and 15°C . PB_o and Ekofisk oil were applied. Q decreased with decreasing temperature. It was obtained again that the entrainment of PB_o was less than with Ekofisk. The oil entrainment versus oil type and temperature is shown also as far as the viscosity ν_o is concerned. The effect of oil type and temperature on the entrainment can be considered as the effect of viscosity: Q increases with decreasing viscosity.

Figure V.86b shows the results of three experiments with different oil surface layer thicknesses $h_o = 0.2, 0.6$ and 1.2 mm. The entrainment was not significantly different, Q seemed independent of h_o . Comparable results were obtained by Milgram et al. (1978) from laboratory measurements on oil dispersion by breaking waves, with oil layer thicknesses of

$h_o = 0.55$ mm and $h_o = 5.5$ mm. The values of Q with $h_o = 5.5$ mm were only half to twice as great as with $h_o = 0.55$ mm, for different types of oil. Milgram explained the independence of Q from h_o by the damping effect of the oil layer on the turbulence, or the generation of larger oil droplets (and resurfacing) for thicker oil films. (We give a different explanation in Section VII.5). The independence of Q from h_o is also in good agreement with the wind wave flume experiments of Bouwmeester and Wallace (1986) with oil film thickness of $h_o = 0.3$ and 0.8 mm (See Section II.2).

V.9 Conclusions from Small-Scale Breaking Wave Experiments

The experiments lead to the following conclusions:

- a) The droplet size distribution $d_o(f)$ of dispersed oil fulfilled the equation

$$N(d_o) = d_o^{-1.3} \quad (5.16)$$

$N(d_o)$ = number of droplets of droplet size interval $0.7 d_o$ to $1.4 d_o$. Equation (5.16) is valid over a large range of droplet sizes down to $d_o = 3 \mu\text{m}$ and is valid for all applied oil types, weathering states, breaking wave periods, temperatures and surface layer thicknesses. Resurfacing of big droplets led to a deviation of the size distribution from the Equation (5.16).

- b) Equation (5.16) indicates the following relation of the oil volume to the various size classes:

$$V_t(d_o) = 1.45 V(d_o) \quad (5.17)$$

$V(d_o)$ = volume of oil droplets in the size interval $0.7 d_o$ to $1.4 d_o$
 $V_t(d_o)$ = volume of oil droplets smaller than $1.4 d_o$.

- c) The oil droplet intrusion depth due to a breaking wave fulfils the Equations:

$$z_1 = 1.5 H_b \quad (5.18a)$$

and

$$z_1 = 3.1 h_{\text{bore}} \quad (5.18b)$$

where H_b = height of breaking wave and
 h_{bore} = bore height of breaking wave

- d) The droplet size distribution $d_o(f)$ and the entrainment Q were independent of the oil layer thickness h_o , in the range $h_o = 0.2$ to 1.2 mm.
- e) A thin layer experiment with $h_o = 0.2$ mm indicated that the oil droplets formed can be much larger than h_o , in agreement with experiments in the grid column. (See Section III).
- f) Total oil entrainment Q_{tot} as well as the entrainment per unit area Q increased with increasing breaking wave energy.
- g) The relative entrainment for different types of oil is given by:

$$Q(PB_o) : Q(PB_{10}) : Q(Eko) = 1 : 0.6 : 2.2$$
- h) Oil entrainment decreased significantly with decreasing temperature.
- i) Rapid emulsification took place in breaking wave conditions.

The preceding conclusions were drawn from the Oil Flume experiments as a separate portion of the present study. The discussion in Section VII integrates the Oil Flume experimental results with the results from the grid column experiments and the large-scale Delta Flume experiments, and leads to quantitative descriptions of the droplet size distributions and the oil entrainment in different circumstances.

VI. LARGE-SCALE EXPERIMENTS ON OIL DISPERSION BY BREAKING WAVES

VI.1 Introduction

Some of the small-scale Oil Flume dispersion experiments with the sampling devices (see Section V.5) were performed in the large-scale Delta Flume as well. The Delta Flume is described in Appendix A.1.3.

The length scaling factor n_l between the Delta Flume and the Oil Flume was $n_l = 10$. Accordingly, the water depth in the Oil Flume (0.43 m) was increased to 4.3 m and the wave height of the breaking waves was about 2 m in the Delta Flume. The experiments on the break-up of an oil layer in the Delta Flume can be considered as full-scale experiments with respect to the water depth and wave heights, but differences exist in the way of generation of the breaking waves. Breaking waves in field conditions are generated by the wind or by waves on a sloping bottom, while the breaking waves in the flume are due to a specific composition of irregular waves from the wave generator. It is assumed that the effect of the breaking waves on oil dispersion in the flume is similar with field conditions if the energy dissipations are equal.

The purpose of the Delta Flume experiments was to compare the more extensive series of experiments in the Oil Flume with measurements where the breaking wave energy per unit area is a factor of 100 larger. Moreover, the turbulence level from the breaking wave in the Delta Flume is of the same order of magnitude as in the grid column experimental conditions.

The Delta Flume was equipped with a wave generator very comparable with that in the Oil Flume. The wave generator in the Delta Flume was fed with the same wave train signal as used in the Oil Flume, but the wave height was amplified with a factor $n_H = 10$ and the wave period with $n_{Tw} = 10^{\frac{1}{2}}$.

VI.2 Experimental Set-up

The performance of the Delta Flume experiments was as similar as possible



FIGURE VI. 1 Measuring section in the Delta Flume

to the Oil Flume experiments, in particular as regards the second series of Oil Flume experiments making use of samplers and microscopic observation of oil droplets. Of course, the length scaling factor $n_1 = 10$ had to be taken into account.

Figure VI.1 is a picture of the measuring section of the flume. The measuring equipment is generally mounted on the movable cart.

Flume water

The flume contained fresh water ($S = 0$) in contradiction with the salt water conditions ($S = 30 \text{ ‰}$) in the Oil Flume. However, it was concluded in the grid column experiments that the salinity of the water does not influence the break-up of oil. Of course, the density of the water influences the buoyancy of the oil droplets and therefore, it influences the resurfacing of the droplets. ($\rho_w = 1000 \text{ kg/m}^3$ in the Delta Flume and $\rho_w = 1025 \text{ kg/m}^3$ in the Oil Flume; see also Section VII.4). The water depth was $h = 4.3 \text{ m}$, compared with $h = 0.43 \text{ m}$ in the Oil Flume.

Oil slicks

The oil films in the small-scale Oil Flume were 2 m long, 0.5 m wide and were generally 0.5 mm thick, the volume was 0.5 litre. Scaling of these oil films with $n_1 = 10$ to Delta Flume dimensions would lead to an infeasible oil volume of 500 litres per experiment. It was decided to use only 50 litres of oil per experiment. The oil must be spread over a length of 10 metres, width of 5 metres (= total width of the flume), and consequently lead to the average thickness of $\bar{h}_o = 1 \text{ mm}$. In the Oil Flume, the oil covered the total water surface in between the desired boundaries. The relatively small volume in the Delta Flume was unable to cover the surface by gravitational spreading after pouring the oil from buckets onto the water surface. (Figure VI.2). Moreover, forced spreading by the application of movable barriers, similar as applied in the Oil Flume, failed to cover the total surface. The application of oil in the experiments took place by pouring the oil from buckets in different spots on the water



FIGURE VI.2 Oil pouring onto the water surface

surface with subsequent restricted gravitational spreading. The surface covering fraction within the boundaries of the slick, S_{cov} , was only 0.25 for Prudhoe Bay oil and $S_{cov} = 0.35$ for the less viscous Ekofisk oil, with mean film thicknesses on the covered spots of 4 and 3 millimetres respectively. Consequently, two discrepancies occurred between the Oil Flume and the Delta Flume as far as the oil films were concerned, the surface covering fractions and the (scaled) film thicknesses were not similar. It was concluded from the Oil Flume investigations that the oil entrainment and droplet size distributions were independent of the film thickness h_0 in the millimetre range. The conclusion will be invalid for oil sheen and, ultimately, uncovered surface ($h_0 = 0$). It is assumed that the droplet size distribution of dispersed oil is independent of h_0 and S_{cov} , while the oil entrainment is independent of h_0 and linearly proportional with S_{cov} .

Breaking waves

Oil dispersion was due to breaking waves, similar to the Oil Flume experiments. Three Oil Flume wave trains (wave 2, wave 3 and wave 5) were scaled up to Delta Flume dimensions by increasing the wave height and wave lengths by a factor 10, and the wave period by a factor $10^{1/2}$. Measurements and calculations of the wave properties in the Delta Flume are described in Section VI.3.

Figure VI.3 shows the breaking of a wave in the oil-covered measuring section. Wave breaking took place over about 26 m with wave 2 and wave 3, and over 18 m with wave 5, while the applied oil slick lengths in the experiments were 10 m. The oil surface slicks were located completely within the areas of wave breaking in contradiction with the Oil Flume experiments where the oil slicks included the wave-breaking trajectories. (The slicks lengths were not scaled with $n_1 = 10$ because of the limited oil volume available in the Delta Flume. The discrepancies in relative lengths of oil slick and wave-breaking trajectory between the Oil Flume and the Delta Flume were taken into account in the entrainment calculations).

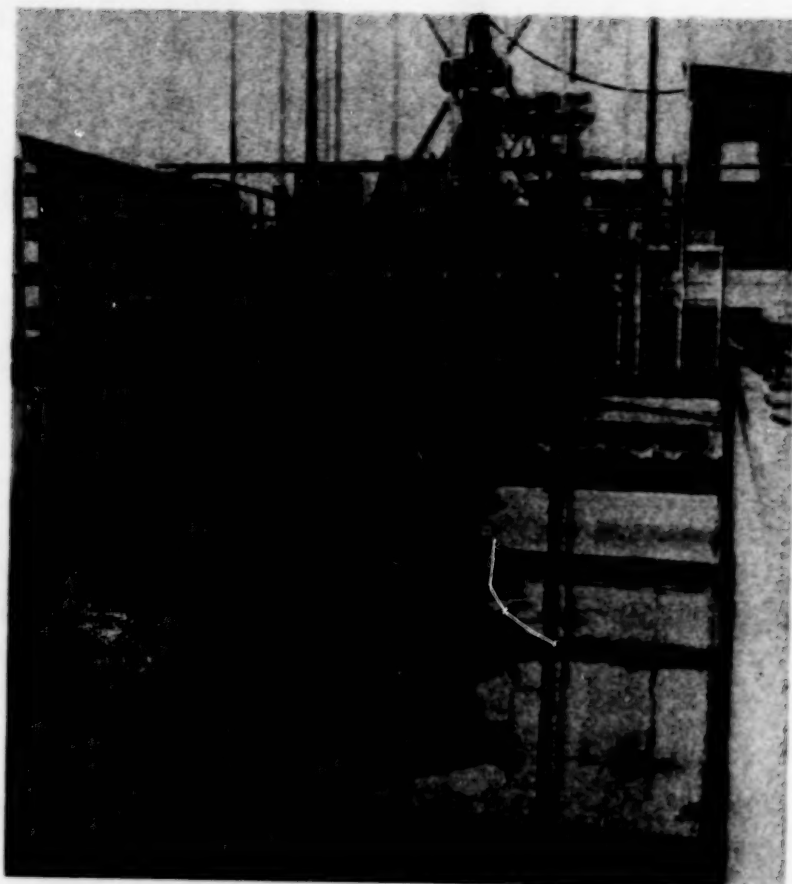


FIGURE VI. 3 Breaking-wave passage through an oil slick

Oil droplet distribution

Oil droplet samples were removed from the Delta Flume with the same samplers as used in the small-scale experiments. The samplers were mounted on a rod at various depths, z , below the water surface. (See Figure VI.5a, b). The rod was mounted on a cart running longitudinally over the flume rims (Figure VI.4). Table VI.1 and Figure VI.6a survey the depths, sampling times and sampling trajectories of the samples taken during the experiments. (Compare Table VI.1 with Table V.5 for the small-scale experiments). Sample "0" was the background sample. The three sets of samples 1A, B, C, 2A, B, C and 3A, B, C were withdrawn while moving the samplers through a part of the oil droplet cloud. The sampling trajectories were chosen to lay completely or almost completely within the cloud. The sampling trajectories were shifted over several metres relative to the location of the surface slick as shown in Figure VI.6a, because it was the experience in the small wave flume experiments that the oil droplet clouds moved "leeward" with the breaking waves. This was confirmed in the Delta Flume experiments by concentration measurements, see Section VI.3.

The oil droplet samples were treated and investigated in the same way as in the Oil Flume measurements.

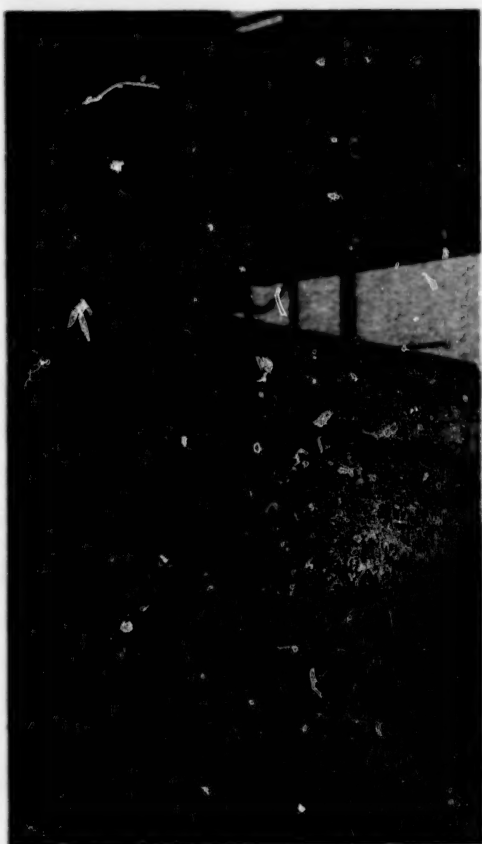
Oil concentration and entrainment

The total amount of dispersed oil per breaking wave was determined from samples withdrawn by tubes at four different depths. (See Figure VI.4 and Figure VI.5c). Table VI.1 and Figure VI.6b survey the depths, sampling times and sampling trajectories of the oil concentration samples. The removal took place along trajectories through the entire oil droplet cloud. The samples were collected in 0.6 litre bottles for oil concentration measurement by infra-red spectroscopy.

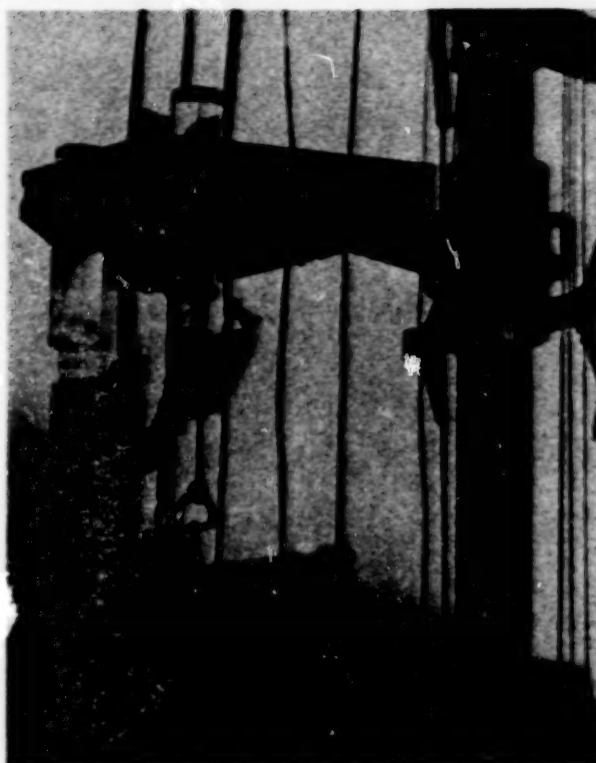


↑	↑	↑
rod with oil droplet samplers	rod with flow velocity and turbulence meters	rod with large-size oil droplet samplers (not used) and tubes for oil concentration sampling

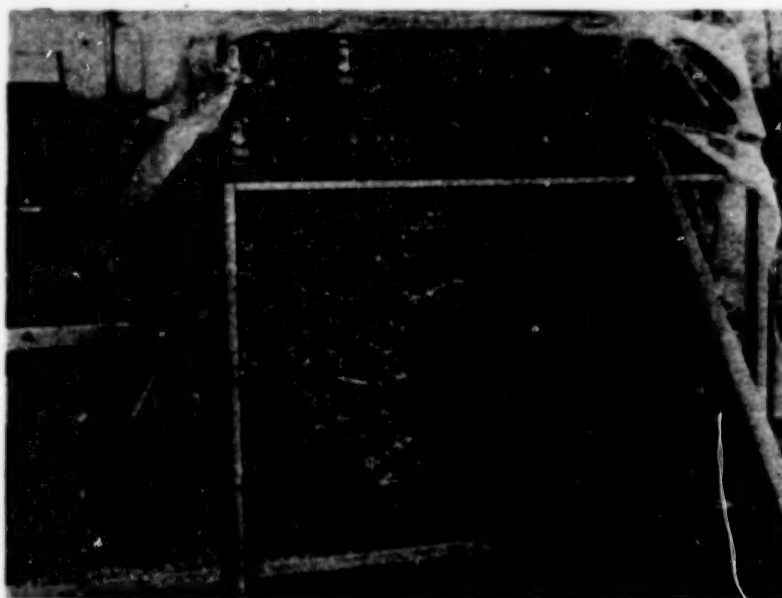
FIGURE VI.4 Measuring equipment before submerging



a) samplers and flow
velocity meters



b) series of samplers for given depth
and different sampling times

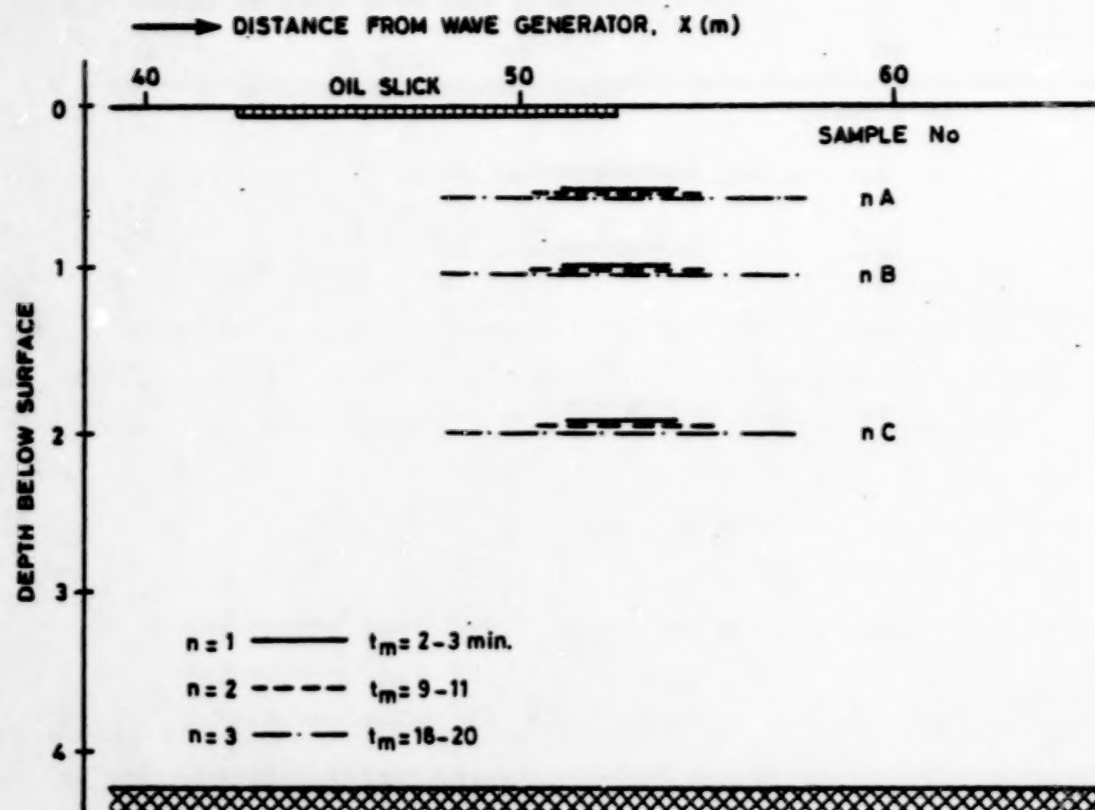


c) pumps, tubes and bottles for oil
concentration sampling

FIGURE VI.5 Details of measuring equipment

Table VI.1 Oil droplet samples and oil concentration samples

sample	depth below water surface z (m)	mean sampling time t_m (minutes)	period of sampling t_m (minutes)	sampling tra- jectory length (m) ($u_c = 0.08$ m/s)
oil droplet samples:				
0	variable	< 0		
1A	0.50	} 2½	2 + 3	4.8
1B	1.00			
1C	2.00			
2A	0.50	} 10	9 + 11	9.6
2B	1.00			
2C	2.00			
3A	0.50	} 19	18 + 20	9.6
3B	1.00			
3C	2.00			
oil concentration samples:				
A1,A2,A3	0.5	15	13 + 17	19.2
B1,B2,B3	1.0	15	13 + 17	19.2
C1,C2,C3	1.75	15	13 + 17	19.2
D1,D2,D3	3.00	15	13 + 17	19.2



a) oil droplet sampling

b) oil concentration sampling

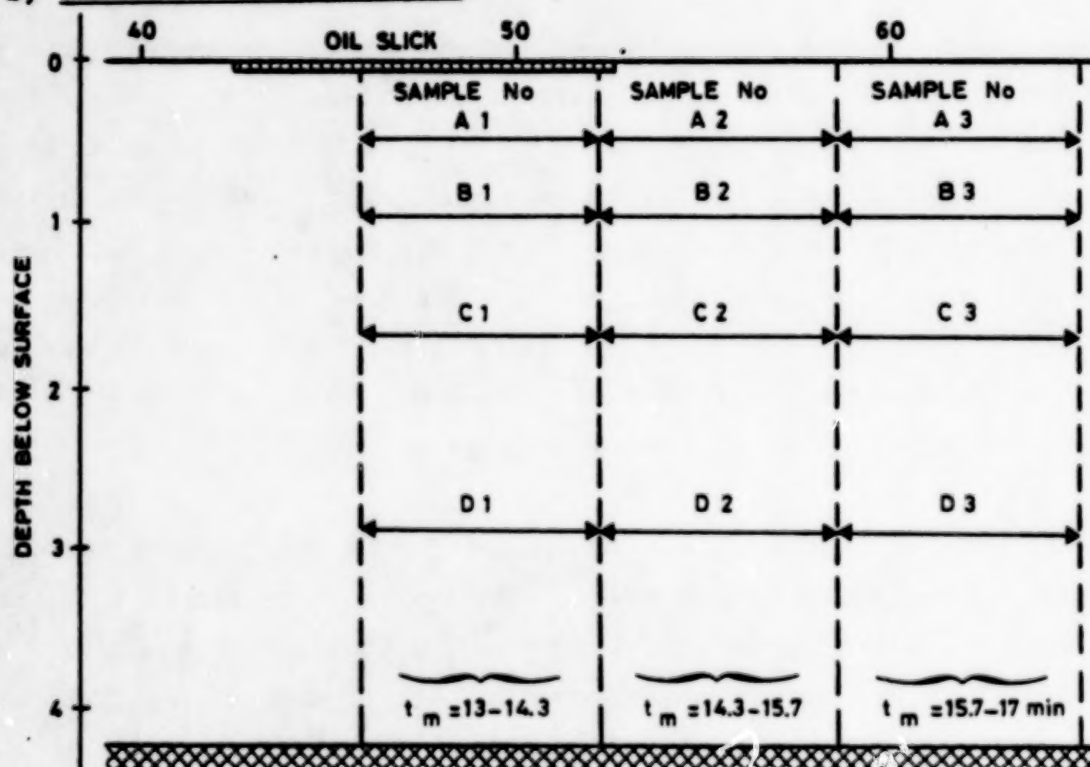


FIGURE VI.6 Trajectories and time of droplet sampling and oil concentration sampling

VI.3 Measurements of Energy Dissipation

Three Oil Flume wave trains were selected and scaled up to Delta Flume values. The wave lengths and wave heights of the Oil Flume parameters were increased by a factor 10 because the length dimensions of the Delta Flume (length, width and water depth) were ten times larger. The wave period T_w and wave propagation velocity c were scaled up by $10^{3/4}$ because c is proportional to $h^{3/4}$ (h = water depth) and T_w is proportional to L/c . The selected wave trains, characterized by their average wave periods were:

$$\text{wave 2 : } T_{w2} = 1.25 \times 10^{3/4} = 3.95 \text{ s,}$$

$$\text{wave 3 : } T_{w3} = 1.2 \times 10^{3/4} = 3.79 \text{ s,}$$

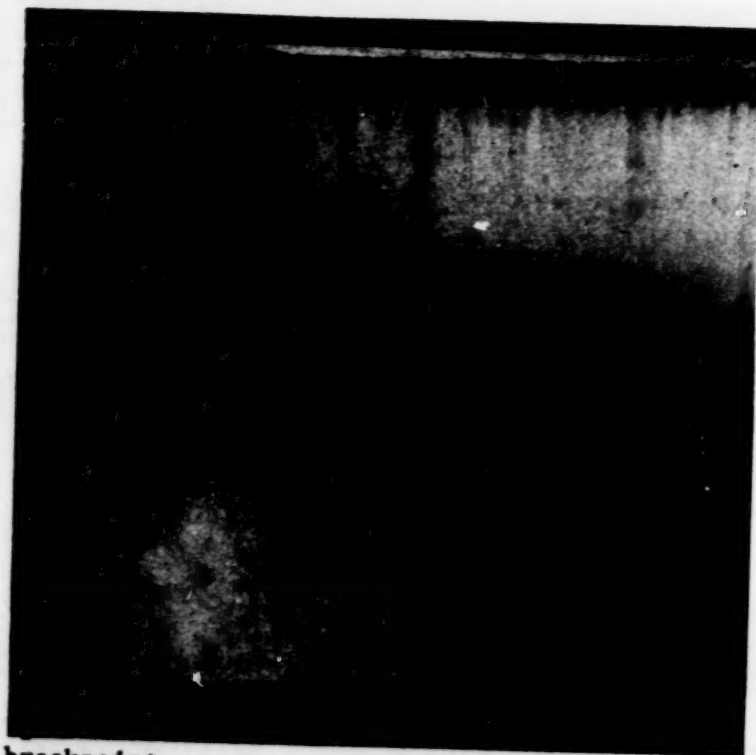
$$\text{wave 5 : } T_{w5} = 1.0 \times 10^{3/4} = 3.16 \text{ s.}$$

The water depth in the flume was 4.3 m. Fresh water was used.

Expressions were derived in Section V.3.1 to calculate the energy dissipation. The measurements of breaking-wave energy dissipation in the Oil Flume were described in Section V.3.2. Similar measurements in the Delta Flume are discussed next.

Two wave-height meters were placed before and beyond the breaker zone at distances of 29 m and 65 m from the wave generator. A third wave height meter was placed as close as possible to the point of initial breaking of the wave trains at 39 m from the wave generator. T_w and H_b were derived from the recordings of the meter at 39 m. The parameters f , L and c were calculated from T_w , H_b and h by applying short wave theory. Following the same method used with the Oil Flume experiments, the signals of the two outer meters were time-integrated to define the integrated power spectra of the wave trains before and beyond the breaker zone.

The bore covered length l_b was determined from visual observation. The parameter t_b was calculated from l_b/c . The average bore height h_{bore} was determined by taking pictures of the bore from the side of the flume, at the point where the bore was most powerful. The Figures VI.7a, VI.8a and VI.9a show the photographs of the waves 2, 3 and 5 respectively. The average bore height $\bar{h}_{\text{bore}}$ was estimated to be half the maximum bore



a)

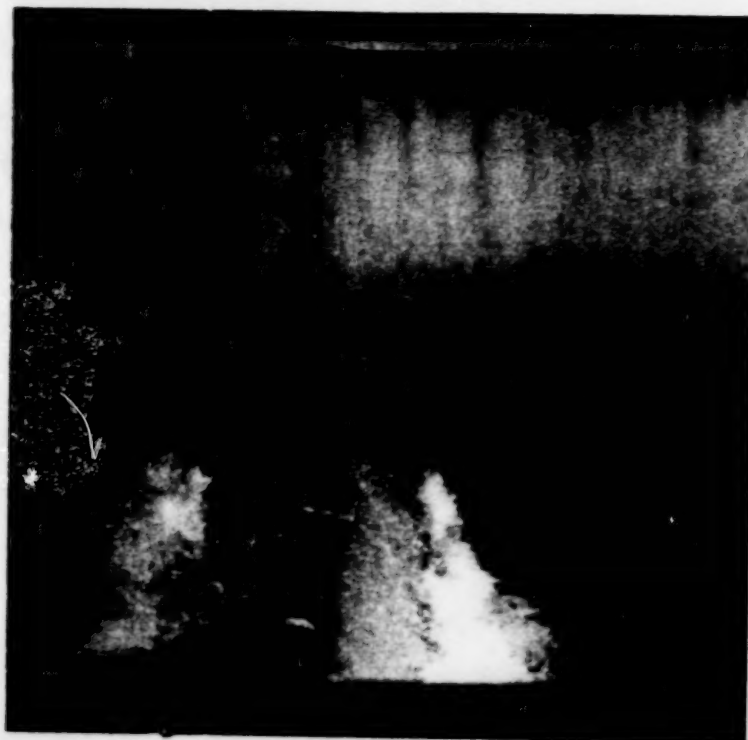
breakpoint



b)

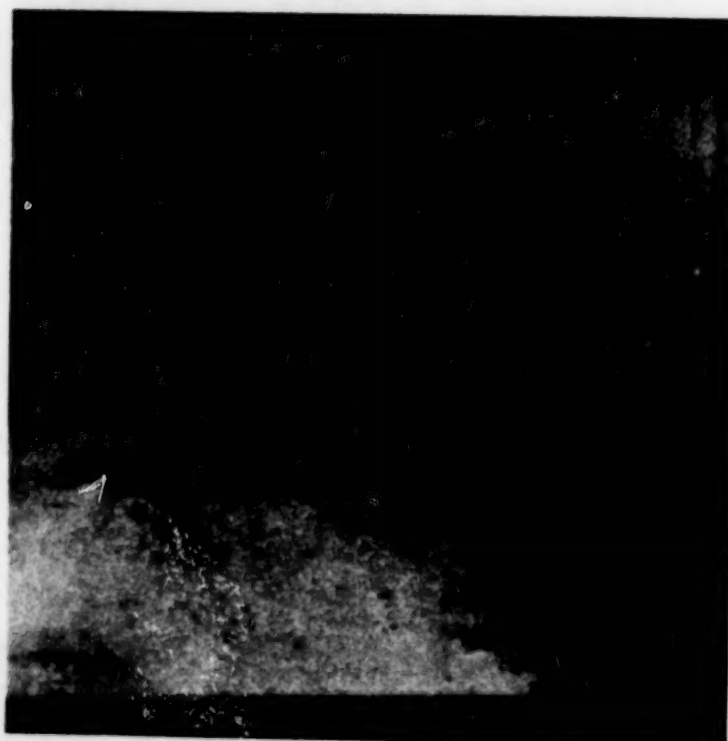
bore

FIGURE VI.7 Breaking wave 2 in delta flume



a)

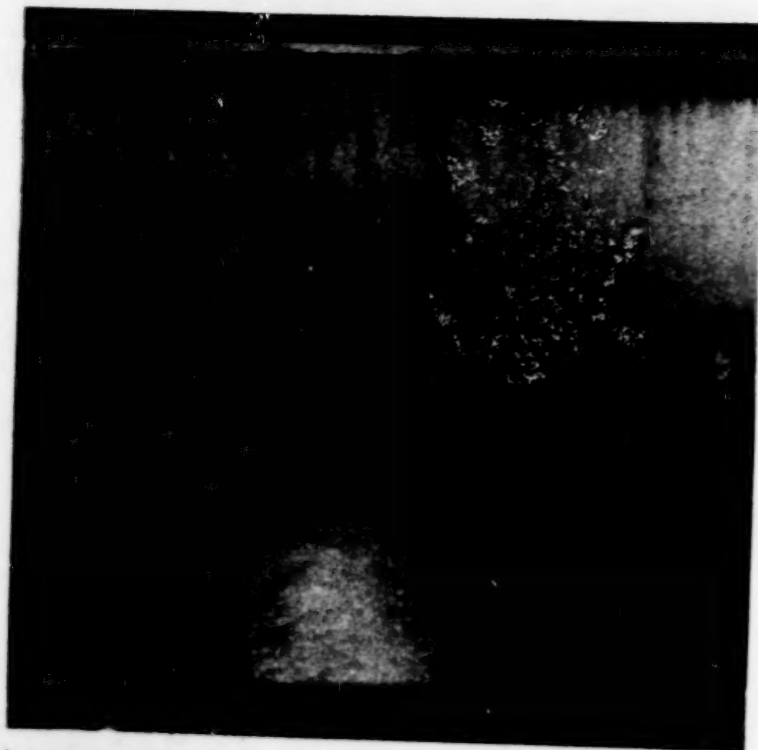
breakpoint



b)

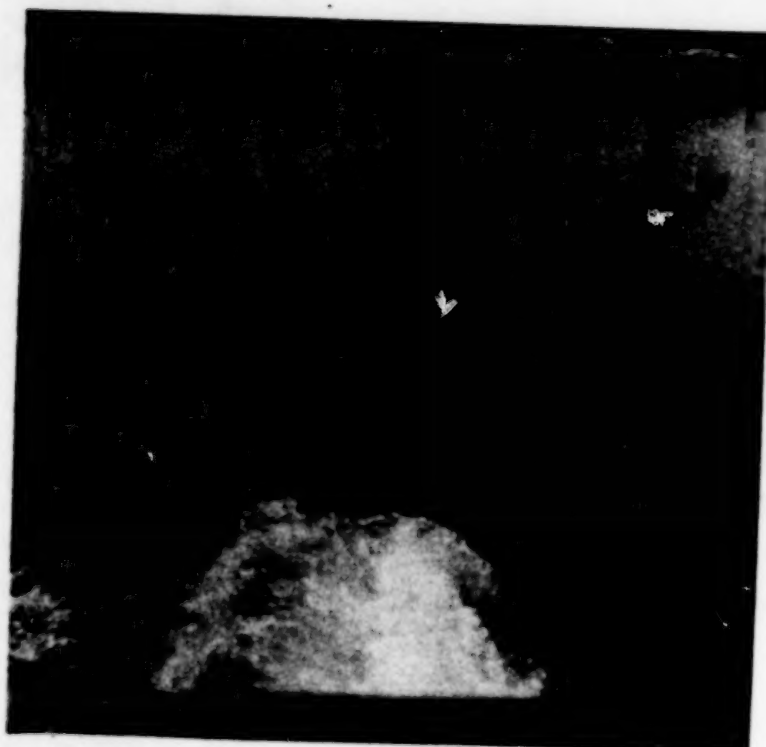
bore

FIGURE VI.8 Breaking wave 3 in delta flume



a)

breakpoint



b)

bore

FIGURE VI. 9 Breaking wave 5 in delta flume

Table VI.2 Results of Delta Flume wave measurements and scaled Oil Flume wave measurements

parameter	units	scaling factor Oil Flume ---> Delta Flume	scaled values (see Table V.1)			measured values		
			wave train number			wave train number		
			2	3	5	2	3	5
PS_I	m^2s	$100\sqrt{10}$	4.30	3.60	1.45	2.71	2.19	1.09
PS_{II}	m^2s	$100\sqrt{10}$	3.95	3.38	1.36	2.39	1.93	0.93
h	m	10	4.3	4.3	4.3	4.3	4.3	4.3
h_1	m	10	3.7	3.5	3.7	3.7	3.7	3.85
h_2	m	10	5.0	5.9	5.3	5.6	5.5	5.25
H_b	m	10	2.3	2.4	1.5	1.9	1.8	1.4
T_w	s	$10^{1/2}$	4.7	4.7	3.5	4.2	4.1	3.5
f	s^{-1}	$0.1 \times 10^{1/2}$	0.2	0.2	0.3	0.2	0.2	0.3
L	m	10	26	26	18	22.5	22.5	17.2
c	m/s	$10^{1/2}$	5.7	5.4	5.1	5.4	5.5	4.9
n_w	-	-	0.8	0.8	0.7	0.7	0.7	0.6
$l_b \bar{h}_{bore}$	m^2	100	10.3	11.6	5.6	8.5	5.9	2.5
l_b	m	10	18.3	18.7	13.4	21.3	15.4	10.0
$\bar{h}_{bore}$	m	10	0.6	0.6	0.4	0.4	0.35	0.25
t_b	s	$10^{1/2}$	3.2	3.5	2.9	3.9	2.8	2.0
D_b	J/m	1000	16000	9000	3000	12000	10000	5000
E_k	J/kg	10	1.5	0.8	0.6	1.4	1.7	1.9
t_s	s	$10^{1/2}$	3.9	5.6	4.2	1.9	1.5	0.9
E_{hj}	J/m	$100 \times 10^{1/2}$	40000	38000	9000	19000	17000	7000
α	-	-	0.2	0.1	0.1	0.2	0.2	0.3
$\alpha^{1/3} H$	m	10	1.2	1.0	0.7	1.0	1.1	1.0
D_{ba}	J/m^2	100	900	500	200	600	600	500
$\frac{E_{hj}}{c}$	J/m^2	100	6900	7100	1800	3500	3000	1400
e	J/m^3s	$10^{1/2}$	400	100	100	400	600	900
$\frac{E_{hj}}{c h_{bore} t_s}$	J/m^3s	$10^{1/2}$	3000	2000	1100	2600	3000	2700

height, assuming a diamond-shaped volume occupied by the bore as a function of time (see Figures V.12 to V.18). The parameter h_2 has also been determined from pictures of the bore, after the initial breaking point. These pictures are shown in Figures VI.7b, VI.8b and VI.9b. The parameter h_1 then was calculated from $(h_2 - H_b)$. Finally t_s was calculated from the halflife of turbulent kinetic energy according to Equation (V.15).

The results of the Delta Flume experiments are gathered in Table VI.2, right hand side. On the left hand side the results of the Oil-Flume experiments are presented, scaled up to Delta Flume values. The scaling factors used are given as well.

The data in Table VI.2 demonstrate that the measured wave parameters T_w , H , L , and c were up to 25 percent smaller than the scaled Oil Flume values. Differences in the bore covered length l_b were within the same range for wave 3 and 5, while l_b of wave 2 was larger than the Oil Flume value. The measured bore heights $\bar{h}_{bore}$ were smaller than the Oil Flume values by 35% to 55%. Because water depth and wave train characteristics were scaled rather well, it is probable that $\bar{h}_{bore}$ was estimated too low. Errors in l_b and $\bar{h}_{bore}$ also lead to errors in the bore volume $l_b \bar{h}_{bore}$ and the characteristic time scale t_b , and eventually to errors in D_{ba} and e .

The measured energy dissipation per unit width, D_b , decreases from wave 2 to wave 5. The absolute values are in good agreement with the scaled Oil Flume values. The values for D_{ba} are in the same order of magnitude as the scaled Oil Flume values, but the decreasing tendency from wave 2 to 5 is absent. The values of e are not in good agreement with the scaled Oil Flume values. The lack of similarity between the values of D_{ba} and e for the Delta Flume and the Oil Flume are presumably due to inaccuracies in the measured bore characteristics l_b and $\bar{h}_{bore}$, leading to errors in t_s as well. The presented data must be considered as order of magnitude estimates.

Table VI.3 Measured data of Delta Flume experiments on oil dispersion

Experiment number	F1	F2	F3	F4	F5
Type of oil	PB _o	PB _o	Eko	PB _o	Eko
Applied wave	5	2	2	3	5
D_{ba} (J/m ²)	200	900	900	500	200
s_{cov}	0.25	0.25	0.35	0.25	0.35
Q_{tot} (kg)	0.247	0.387	1.08	0.468	0.710
Q (10 ⁻³ kg/m ²)	4.93	7.73	21.7	9.36	14.2
Dispersed oil/ surface oil (%)	0.50	0.77	2.2	0.94	1.4

The calculated parameter values from the hydraulic jump analog are in reasonable agreement with the scaled Oil Flume values. E_{hj} and E_{hj}/c for waves 2 and 3 are 50% smaller than the Oil Flume values, but the wave characteristics they were based upon (e.g. the wave height H_b) also differ. Comparison of measured values for the energy dissipation and calculated values using the hydraulic jump analog method, shows good overall resemblance, considering the inaccuracies in the measured wave characteristics, l_b and $\bar{h}_{bore}$ in the Delta Flume.

Values for α of about 0.2 were found, in reasonable agreement with the Oil Flume experiments with $\alpha = 0.15$. In the hydraulic jump analog, the factor $\alpha^{1/3} H_b$ is assumed to be equal to the maximum bore height $h_{bore}(max)$, while $h_{bore}(max)$ was approximated by $h_{bore}(max) = 2 \bar{h}_{bore}$ from measurements. The measured values for $\bar{h}_{bore}$ are smaller (see Table VI.2). This supports the assumption that $\bar{h}_{bore}$ was estimated too low in the Delta Flume.

VI.4 Presentation of the Measurements

Table VI.3 summarizes the five experiments performed together with some measured data. PB₀ and Ekofisk oil were used in the experiments. The applied waves were wave 2, wave 3 and wave 5 where the wave numbers refer to the comparable waves in the small-scale experiments. The energy dissipation per unit area in the breaking wave D_{ba} (see Table VI.3) is discussed also in Section VII.

S_{cov} in Table VI.3 refers to the oil covered fraction of the surface within the area of oil application, $10 \times 5 \text{ m}^2$, before the passage of the breaking wave.

The oil droplet samples were treated in the same way as in the Oil Flume experiments. Photographs of the oil droplets and the $N(d_o)$ versus d_o graphs are given in the Figures VI.10 to VI.24.

The measured oil concentrations in various horizontal and vertical loca-

photographs
were not taken

RUN F1 PB₀
 SAMPLES 1 A,B,C
 WAVE 5 T_w = 3.4 s
 TEMPERATURE 12 °C
 OIL LAYER 1.0 mm
 WATERDEPTH 4.3 m
FULL-SCALE EXPERIMENT

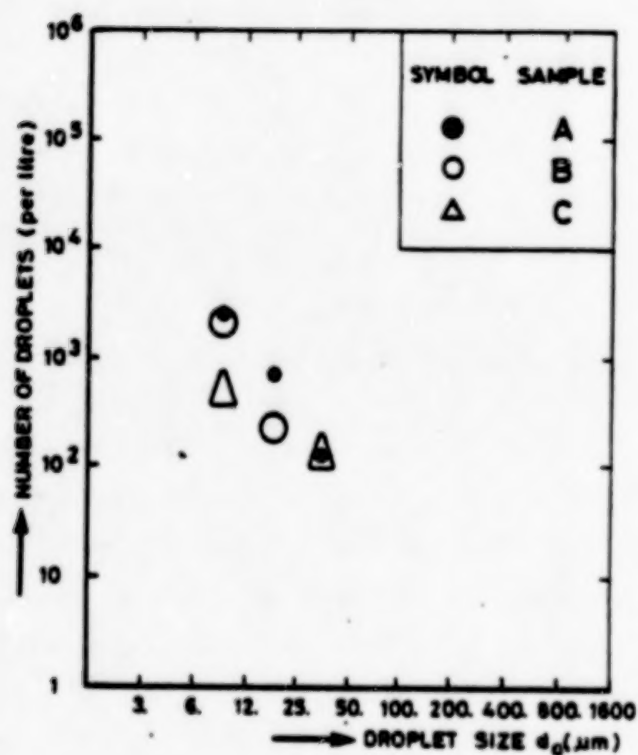
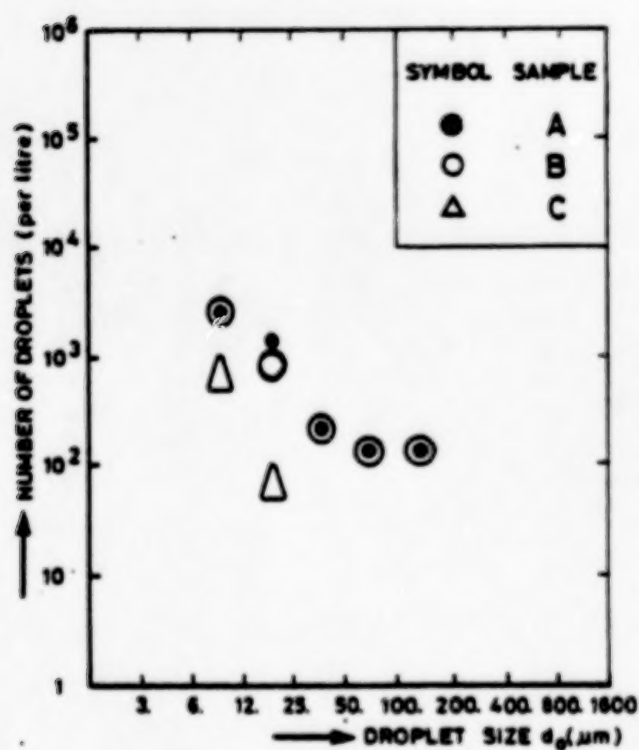


FIG. VI. 10 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.

photographs
were not taken

RUN F1 PB_0
 SAMPLES 2 A,B,C
 WAVE 5 $T_w = 3.4$ s
 TEMPERATURE 12 °C
 OIL LAYER 1.0 mm
 WATERDEPTH 4.3 m
FULL-SCALE EXPERIMENT

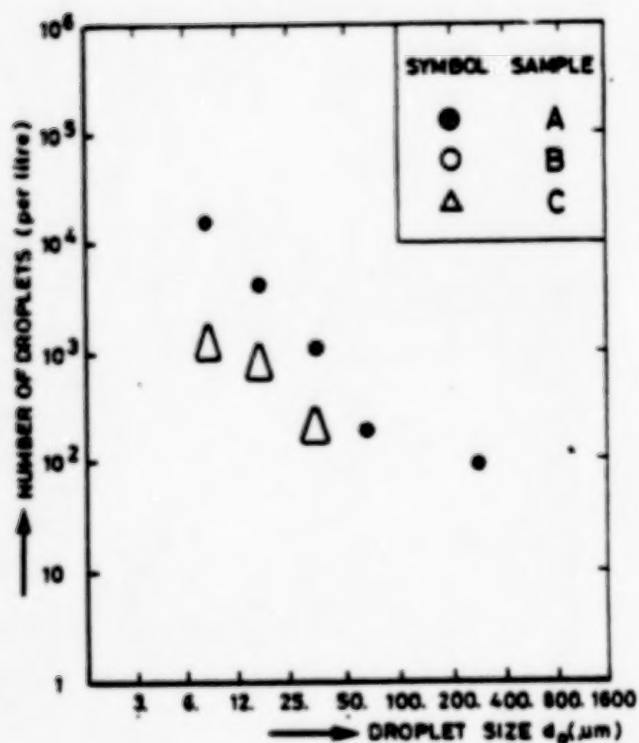


0 1cm

FIG. VI. 11 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.

photographs
were not taken

RUN F1 PB₀
 SAMPLES 3 A,B,C
 WAVE 5 T_w = 3.4 s
 TEMPERATURE 12 °C
 OIL LAYER 1.0 mm
 WATERDEPTH 4.3 m
FULL-SCALE EXPERIMENT



0 1cm

FIG. VI.12 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

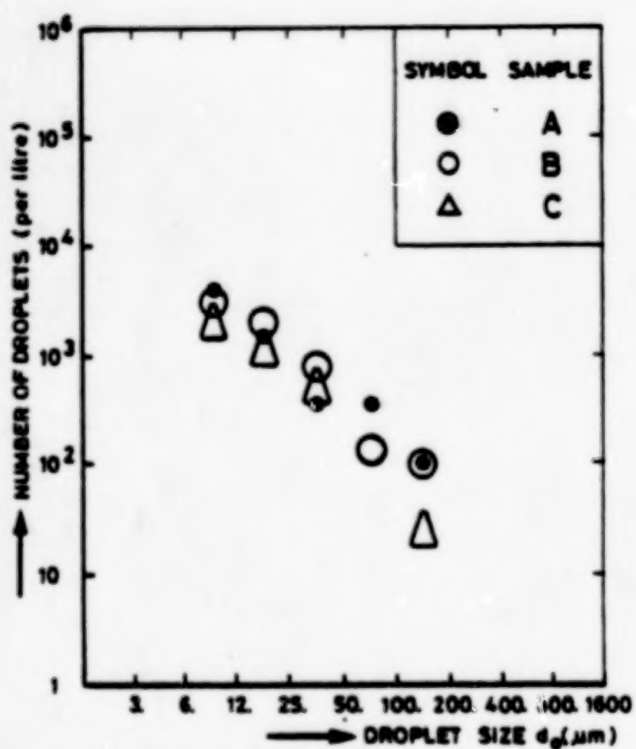


B



C

RUN F2 PB_0
 SAMPLES 1 A,B,C
 WAVE 2 $T_w = 4.2$ s
 TEMPERATURE 12 °C
 OIL LAYER 1.0 mm
 WATERDEPTH 4.3 m
FULL-SCALE EXPERIMENT



0 1cm

FIG. VI. 13 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.

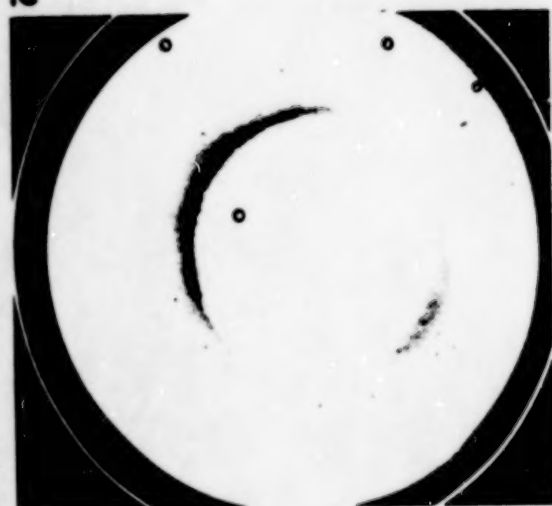


A

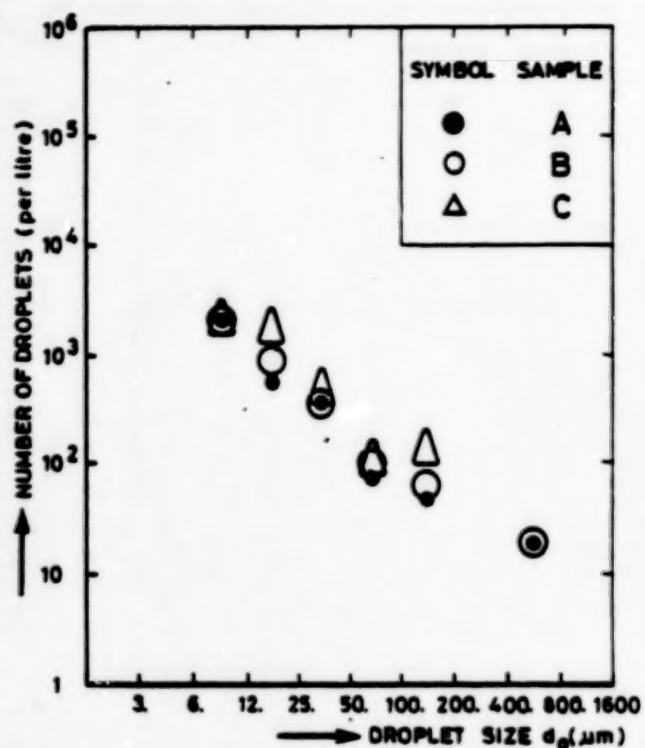


B

C



RUN F2 PB₀
 SAMPLES 2 A, B, C
 WAVE 2 T_w = 4.2 s
 TEMPERATURE 12 °C
 OIL LAYER 1.0 mm
 WATERDEPTH 4.3 m
 FULL-SCALE EXPERIMENT

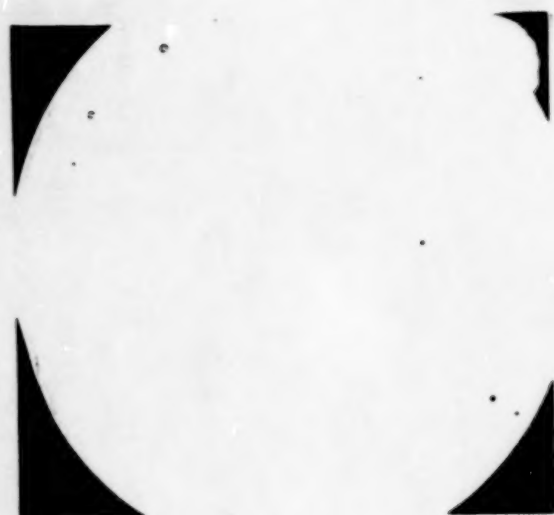


0 1 cm

FIG. VI. 14. OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

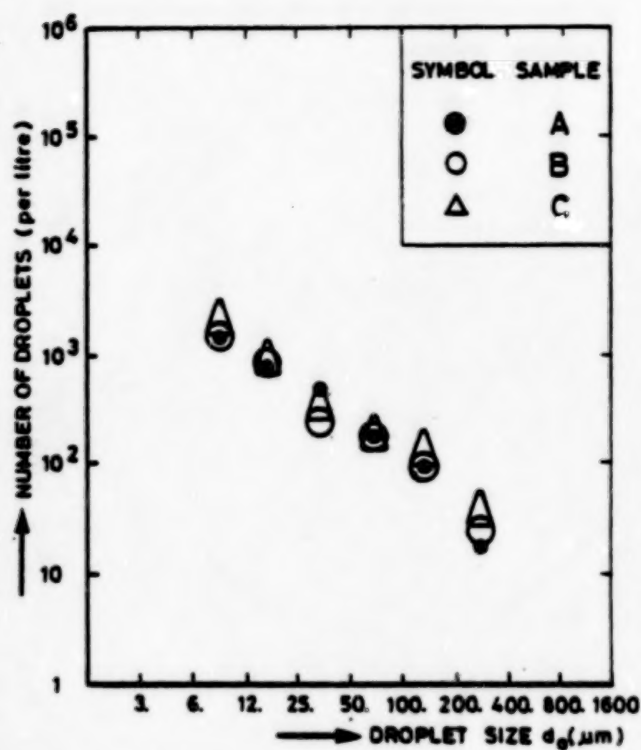


B



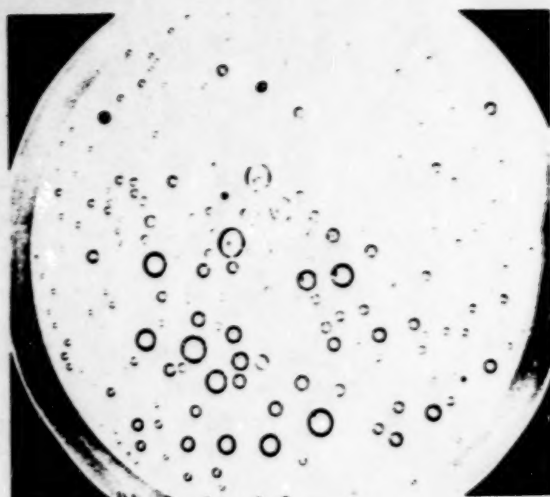
C

RUN F2 PB_0
 SAMPLES 3 A, B, C
 WAVE 2 $T_W = 4.2$ s
 TEMPERATURE 12 °C
 OIL LAYER 1.0 mm
 WATERDEPTH 4.3 m
 FULL-SCALE EXPERIMENT

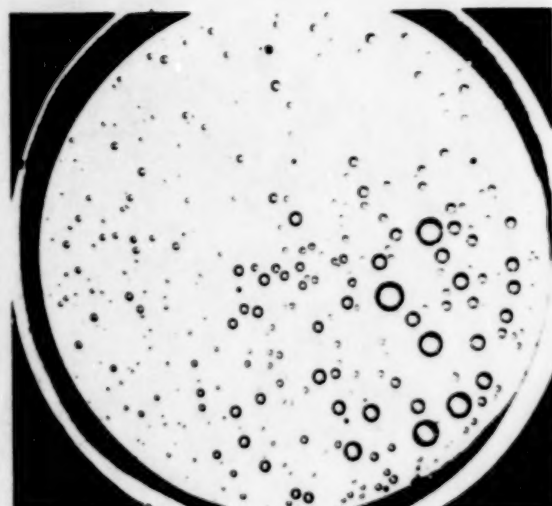


0 1cm

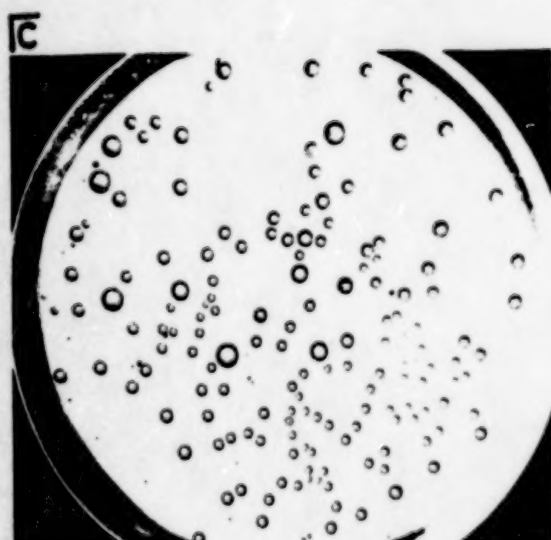
FIG. VI. 15 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

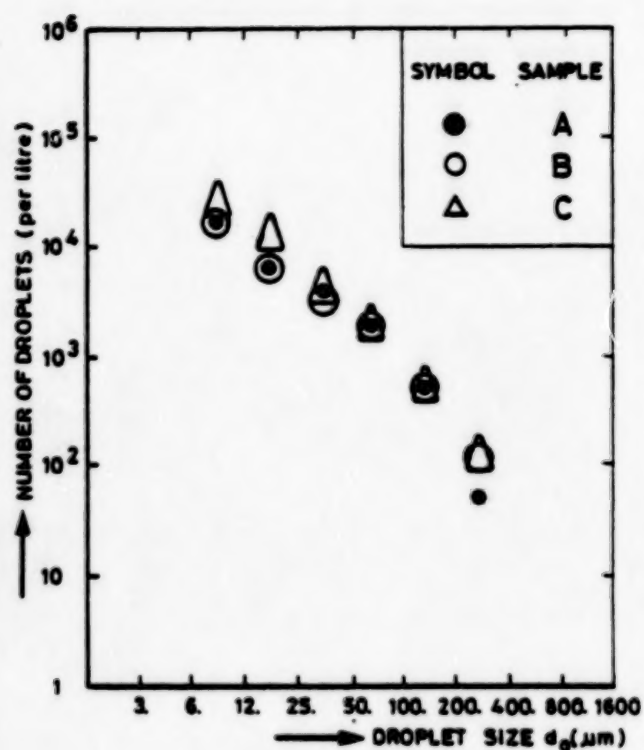


B



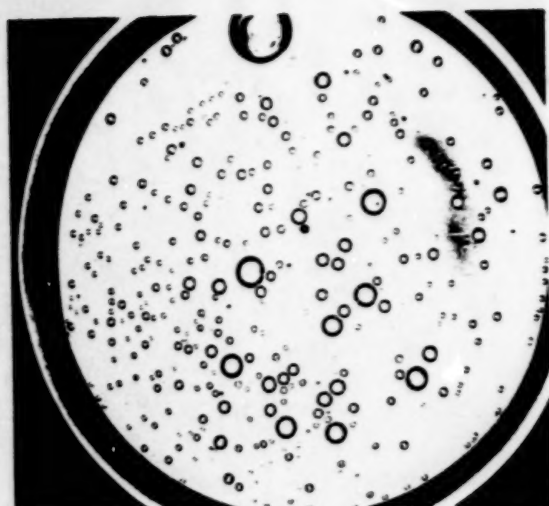
C

RUN F3 Eko
 SAMPLES 1 A,B,C
 WAVE 2 $T_w = 4.2$ s
 TEMPERATURE 12 °C
 OIL LAYER 1.0 mm
 WATERDEPTH 4.3 m
FULL-SCALE EXPERIMENT

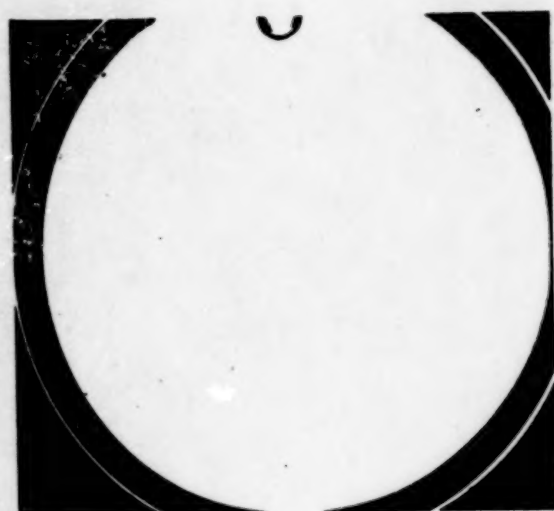


0 1cm

FIG. VI.16 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A



B

RUN F3 Eko
 SAMPLES 2 A,B
 WAVE 2 $T_W = 4.2$ s
 TEMPERATURE 12 °C
 OIL LAYER 1.0 mm
 WATERDEPTH 4.3 m
FULL-SCALE EXPERIMENT

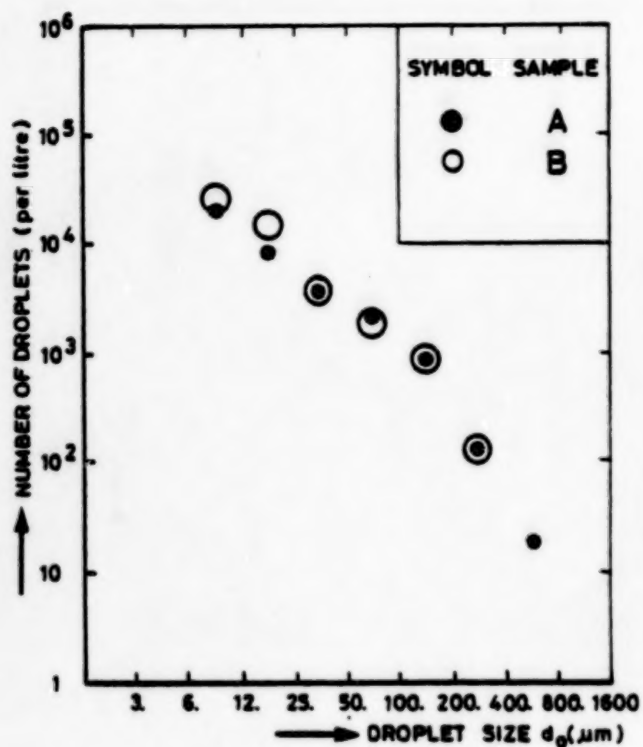
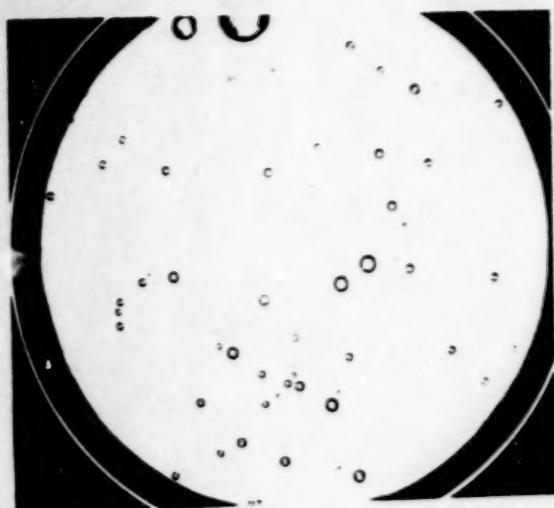


FIG. VI.17 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.

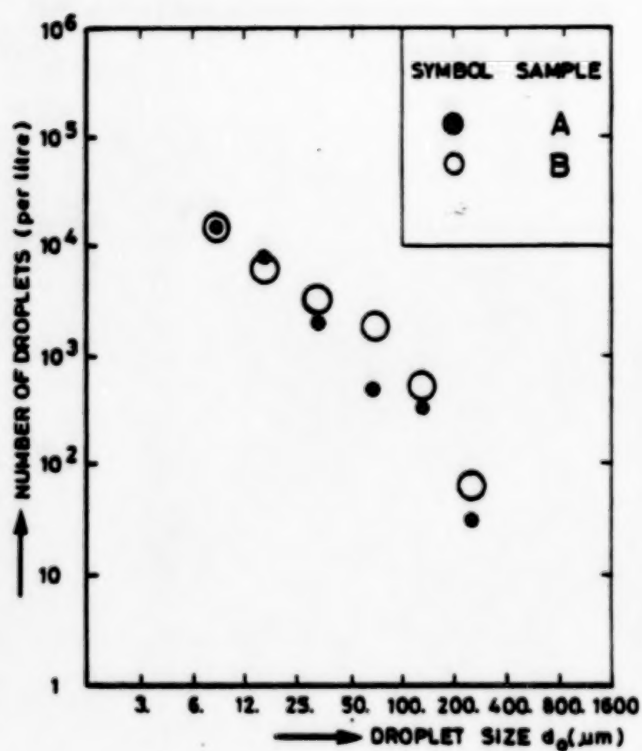


A



B

RUN F3 Eko
 SAMPLES 3 A,B
 WAVE 2 $T_w = 4.2$ s
 TEMPERATURE 12°C
 OIL LAYER 1.0 mm
 WATERDEPTH 4.3 m
FULL-SCALE EXPERIMENT

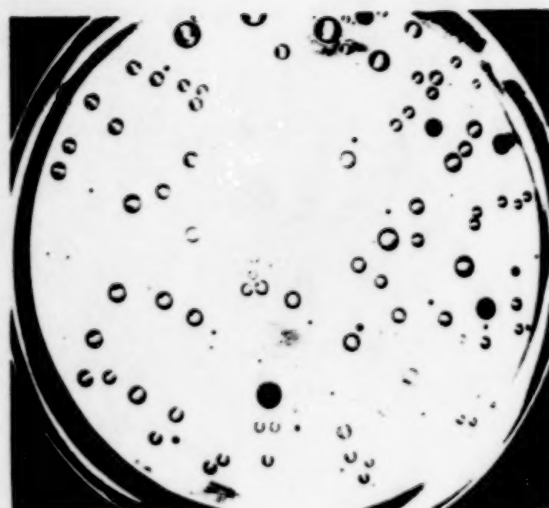


0 1cm

FIG. VI. 18 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

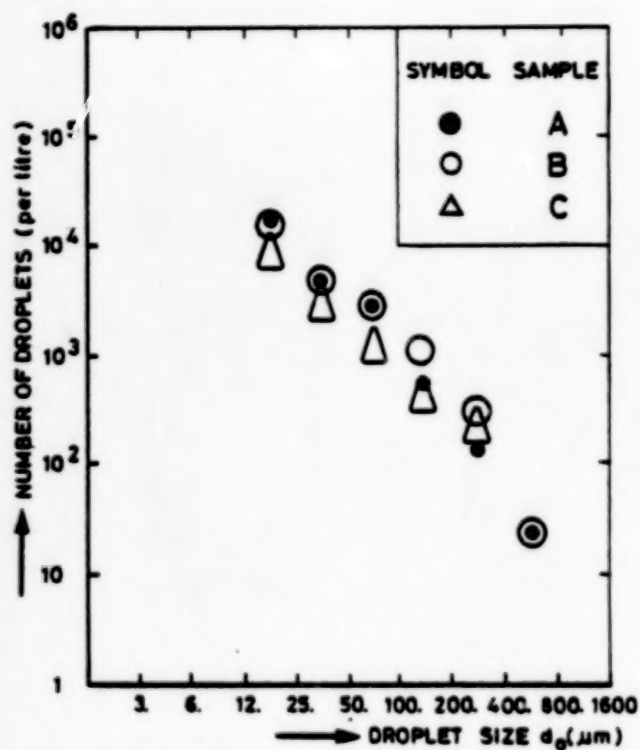


B



C

RUN F4 PB_0
 SAMPLES 1 A, B, C
 WAVE 3 $T_w = 4.1$ s
 TEMPERATURE 12°C
 OIL LAYER 1.0 mm
 WATERDEPTH 4.3 m
FULL-SCALE EXPERIMENT



0 1cm

FIG. VI. 19 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

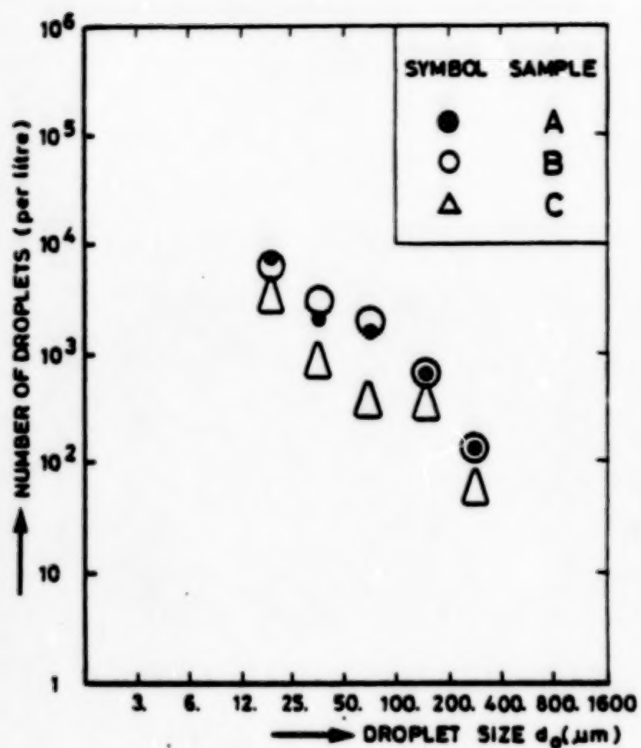


B



C

RUN F4 PB₀
 SAMPLES 2 A,B,C
 WAVE 3 T_w = 4.1 s
 TEMPERATURE 12 °C
 OIL LAYER 1.0 mm
 WATERDEPTH 4.3 m
 FULL-SCALE EXPERIMENT



0 1cm

FIG. VI. 20 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

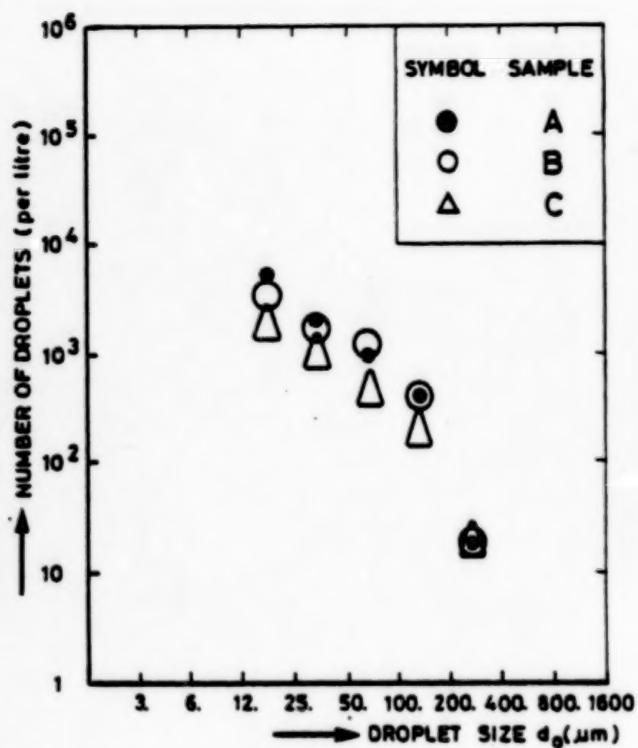


B

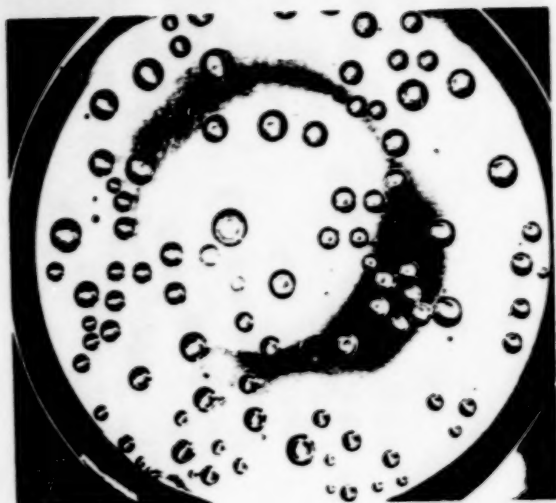


FIG. VI. 21 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.

RUN F4 PB₀
 SAMPLES 3 A,B,C
 WAVE 3 T_w = 4.1 s
 TEMPERATURE 12 °C
 OIL LAYER 1.0 mm
 WATERDEPTH 4.3 m
FULL-SCALE EXPERIMENT



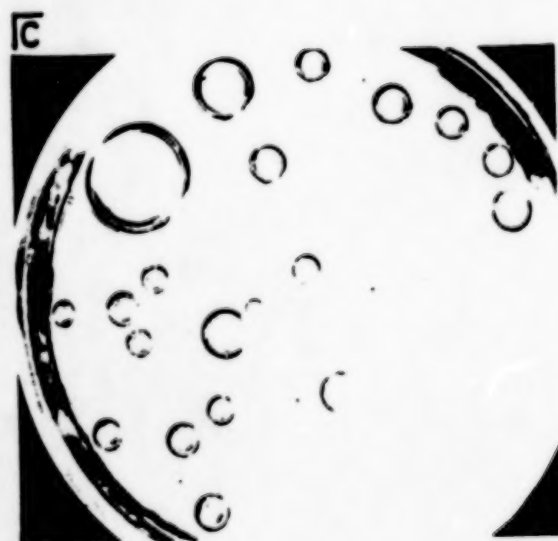
0 1cm



A

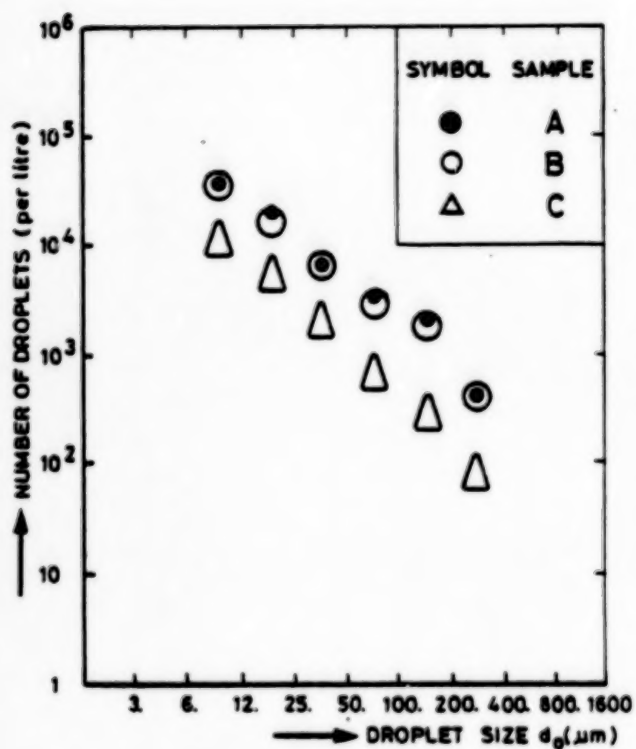


B



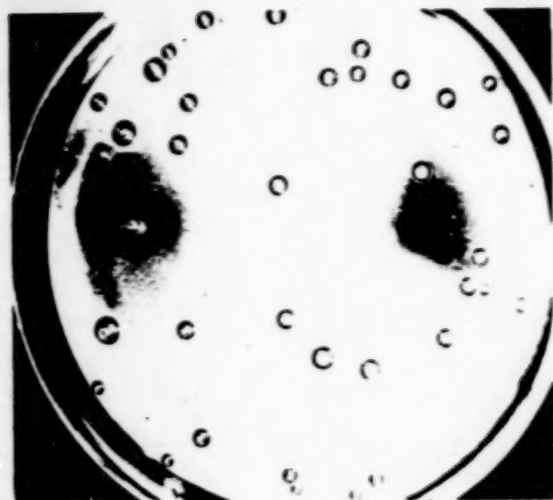
C

RUN F5 Eko
 SAMPLES 1 A,B,C
 WAVE 5 $T_w = 3.4$ s
 TEMPERATURE 12 °C
 OIL LAYER 1.0 mm
 WATERDEPTH 4.3 m
FULL-SCALE EXPERIMENT

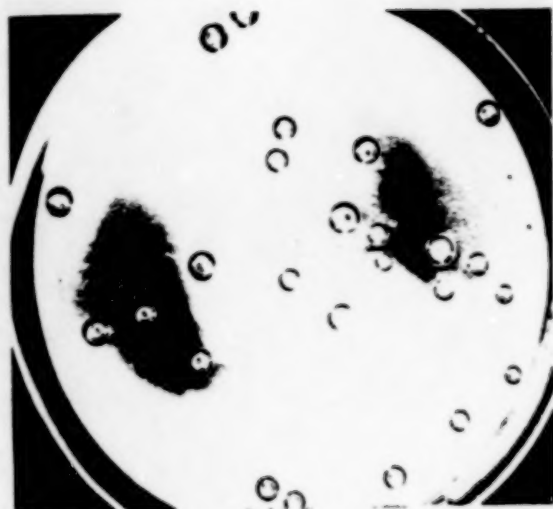


0 1cm

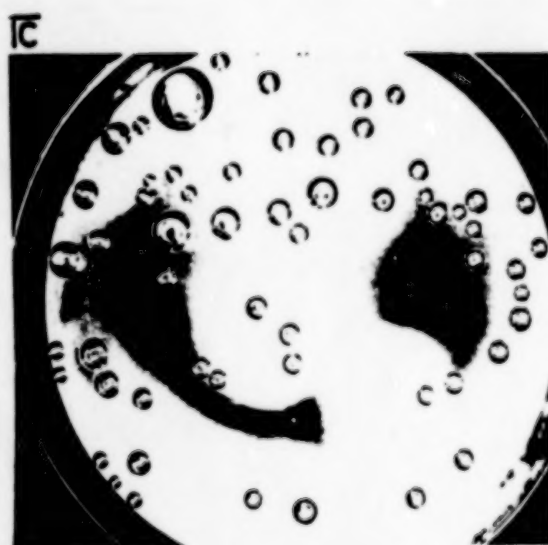
FIG. VI. 22 OIL DROPLETS ,DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A



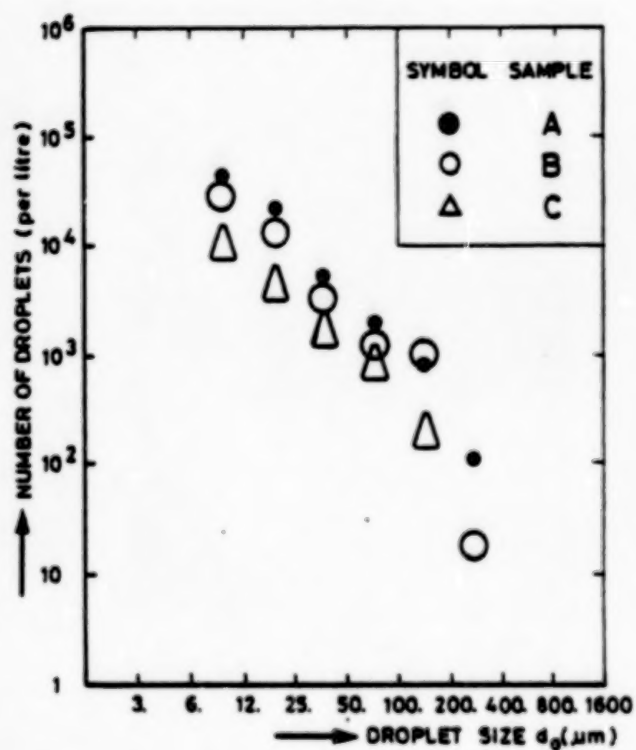
B



C

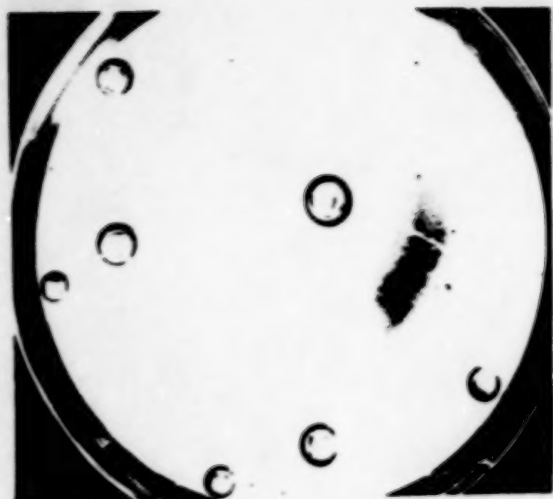
RUN F5 Eko
 SAMPLES 2 A,B,C
 WAVE 5 $T_w = 3.4$ s
 TEMPERATURE 12 °C
 OIL LAYER 1.0 mm
 WATERDEPTH 4.3 m

FULL-SCALE EXPERIMENT

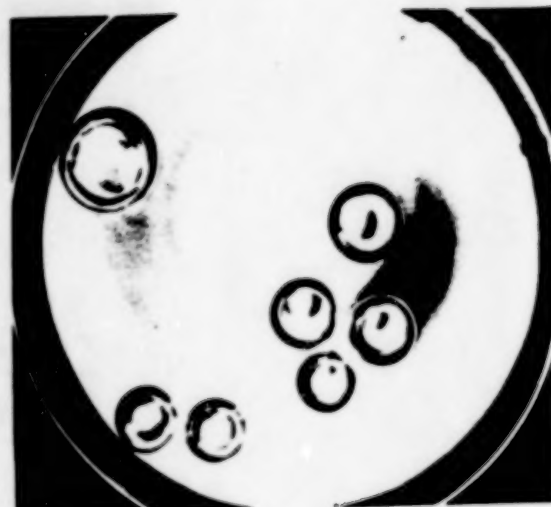


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FIG. VI. 23 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.



A

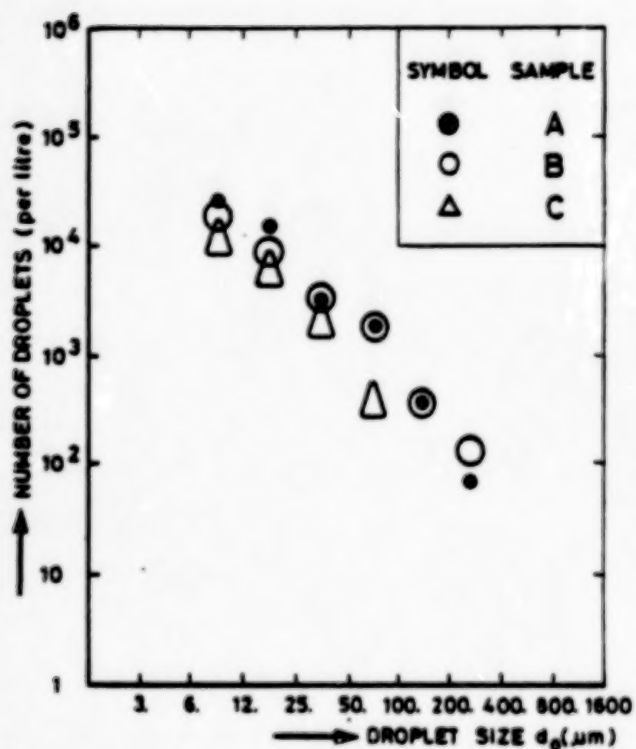


B



C

RUN F 5 Eko
 SAMPLES 3 A,B,C
 WAVE 5 $T_w = 3.4$ s
 TEMPERATURE 12 °C
 OIL LAYER 1.0 mm
 WATERDEPTH 4.3 m
FULL-SCALE EXPERIMENT



0 1cm

FIG. VI. 24 OIL DROPLETS DISTRIBUTION IN BREAKING WAVE EXPERIMENTS.

tions in the dispersed oil clouds, at $t_m = 15$ minutes after the passages of the breaking waves, are given in Table VI.4 and visualized in the Figures VI.25 to VI.29 (See also the definition sketch in Figure VI.6b).

Table VI.5 lists the values of the following dispersion parameters derived from the measured oil concentrations and droplet size distributions:

- a) Q_{tot} is the total amount of dispersed oil at 15 minutes after the passage of the breaking wave. Q_{tot} was obtained from integration of the oil concentration over the flume volume. (The sampled flume section indicated in Figure VI.6b contained the entire cloud of dispersed oil droplets. It was supposed that the concentrations were homogeneous over the width of the flume. Therefore, the integration was conducted in fact by summation of all measured concentrations multiplied with the relevant surrounding volumes).
- b) The ratio between Q_{tot} and the original volume of the surface slick gives an indication of the low fraction of dispersed oil, (at $t_m = 15$ minutes).
- c) $Q_{tot} (m^2, S_{cov} = 1)$ is the volume of dispersed oil per unit surface area that should be found in the experiments if the surface was completely covered with oil. This parameter is useful in the final parameterization of oil entrainment.
- d) The maximum droplet size d_{max} found at $t_m = 15$ minutes was $d_m = 500 \mu m$ for PB oil and $d_m = 350 \mu m$ for Ekofisk oil. Bigger droplets were resurfaced. These values were defined partly from the measured droplet size distribution and partly from the requirement that the ratio between d_{max} for PB and d_{max} for Ekofisk should be about 1.3 due to the buoyancy difference of these types of oil.
- e) The intrusion depth z_1 was derived from the oil concentration measurements, $C_o(z)$, at various depths and from the droplet size distributions at various depths. z_1 was taken as the depth where $C_o(z_1)$ was almost zero and where the number of droplets $N(d_o)$ for small values of d_o is considerably lower than at locations closer to the surface. (Note that $C_o(z)$ always increases with decreasing z due to resurfacing of large droplets, while $N(d_o)$ for small droplets is almost homogeneous over the depth of intrusion.

Table VI.4 Oil concentration data, C_o , at $t_m = 15$ minutes in the Delta Flume experiments (C_o in g/m^3).

Sample No.	Experiment F1			Sample No.	Experiment F2		
	1	2	3		1	2	3
A	0.30	2.28	2.64	A	0.46	3.17	2.16
B	0.00	1.09	1.12	B	1.10	2.02	1.85
C	0.13	1.42	0.90	C	0.37	1.52	1.61
D	0.10	0.00	0.00	D	0.37	1.06	0.83
Sample No.	Experiment F3			Sample No.	Experiment F4		
	1	2	3		1	2	3
A	1.22	8.48	11.85	A	2.03	5.03	6.00
B	1.19	5.77	6.86	B	1.16	1.42	2.53
C	0.50	3.73	5.58	C	0.45	0.65	0.40
D	0.13	0.40	0.16	D	0.14	0.13	0.03
Sample No.	Experiment F5						
	1	2	3				
A	5.97	5.51	5.28				
B	1.35	3.27	2.54				
C	1.09	2.11	2.00				
D	0.10	0.23	0.53				

Table VI.5 Dispersion parameters derived from measurements

parameter (values at $t_m = 15$ minutes)	Units	experiment no., oil type, wave				
		F2(PB ₀) wave 2	F3(Eko)	F1(PB ₀) wave 5	F5(Eko)	F4(PB ₀) wave 3
Q_{tot} (mass of dispersed oil)	kg	0.39	1.08	0.25	0.71	0.47
Q_{tot} /surface oil mass	percent	0.77	2.17	0.50	1.43	0.94
Q_{tot}/m^2 ($=Q_{tot}$ per unit surface area)	g/m ²	7.7	21.7	4.9	14.2	9.4
S_{cov}	--	0.25	0.35	0.25	0.35	0.25
$Q_{tot}/(m^2, S_{cov} = 1)$	g/m ²	30.8	62.0	19.6	40.6	37.4
d_{max}	μm	500	350	500	350	500
z_i	m	3.5		2.0		2.0

VI.5 Results and Conclusions

The series of Delta Flume experiments is too restricted to draw conclusions on its own about the influence of oil type and wave period on the dispersion of oil. The large scale experiments are combined in Section VII with the more comprehensive measurements in the grid column and Oil Flume to conclude whether or not the results of these experiments are in agreement and can lead to full scale conclusions.

In any case it was evident from the $N(d_o)$ versus d_o graphs in Figures VI.10 to VI.24 that the droplet size distributions look similar and the maximum droplet sizes observed were equal with the small-scale Oil Flume experiments.

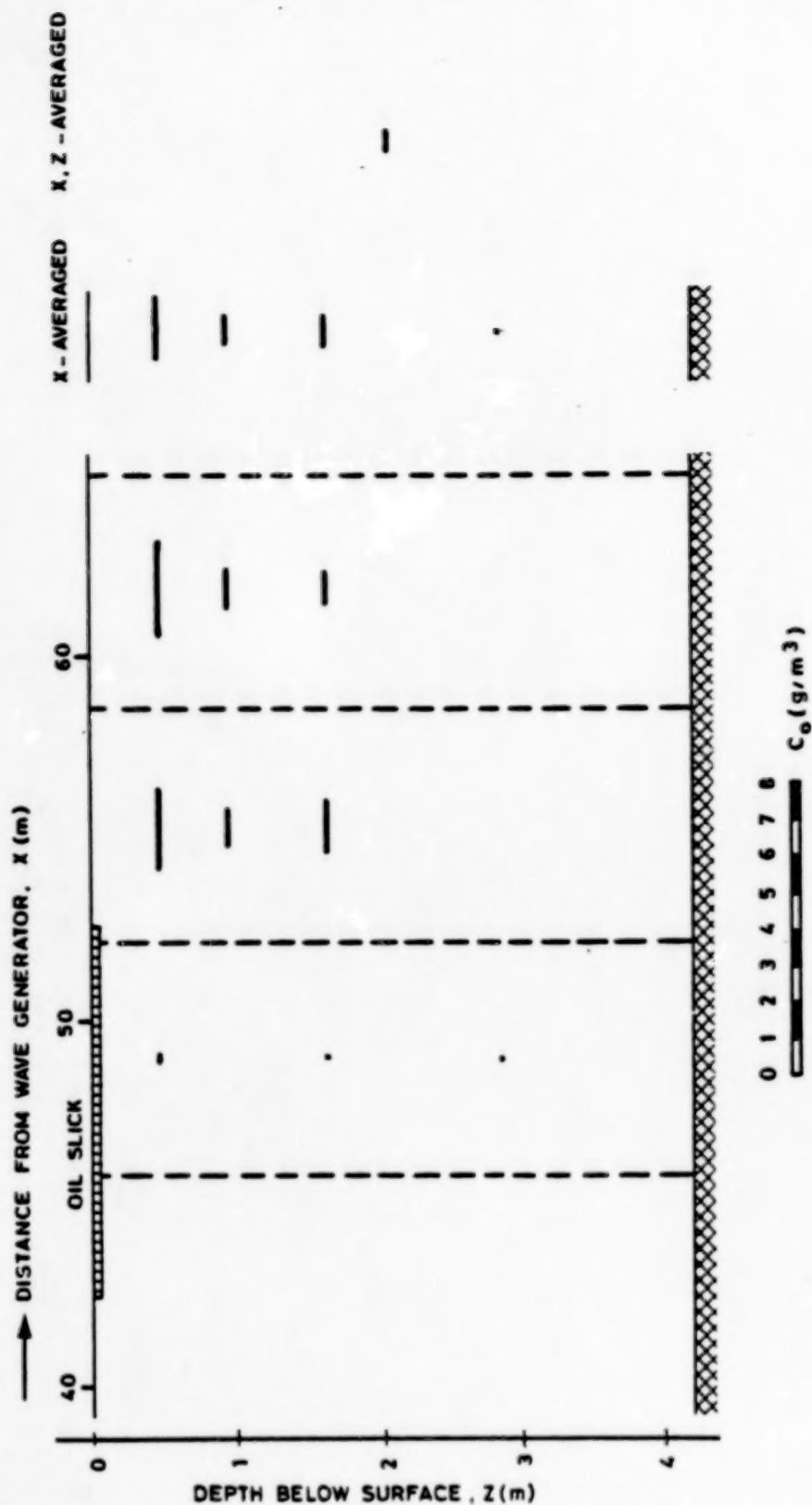


FIGURE VI. 25 Experiment F1. Measured oil concentrations in the dispersed oil cloud at $t_m = 15$ minutes after the breaking wave

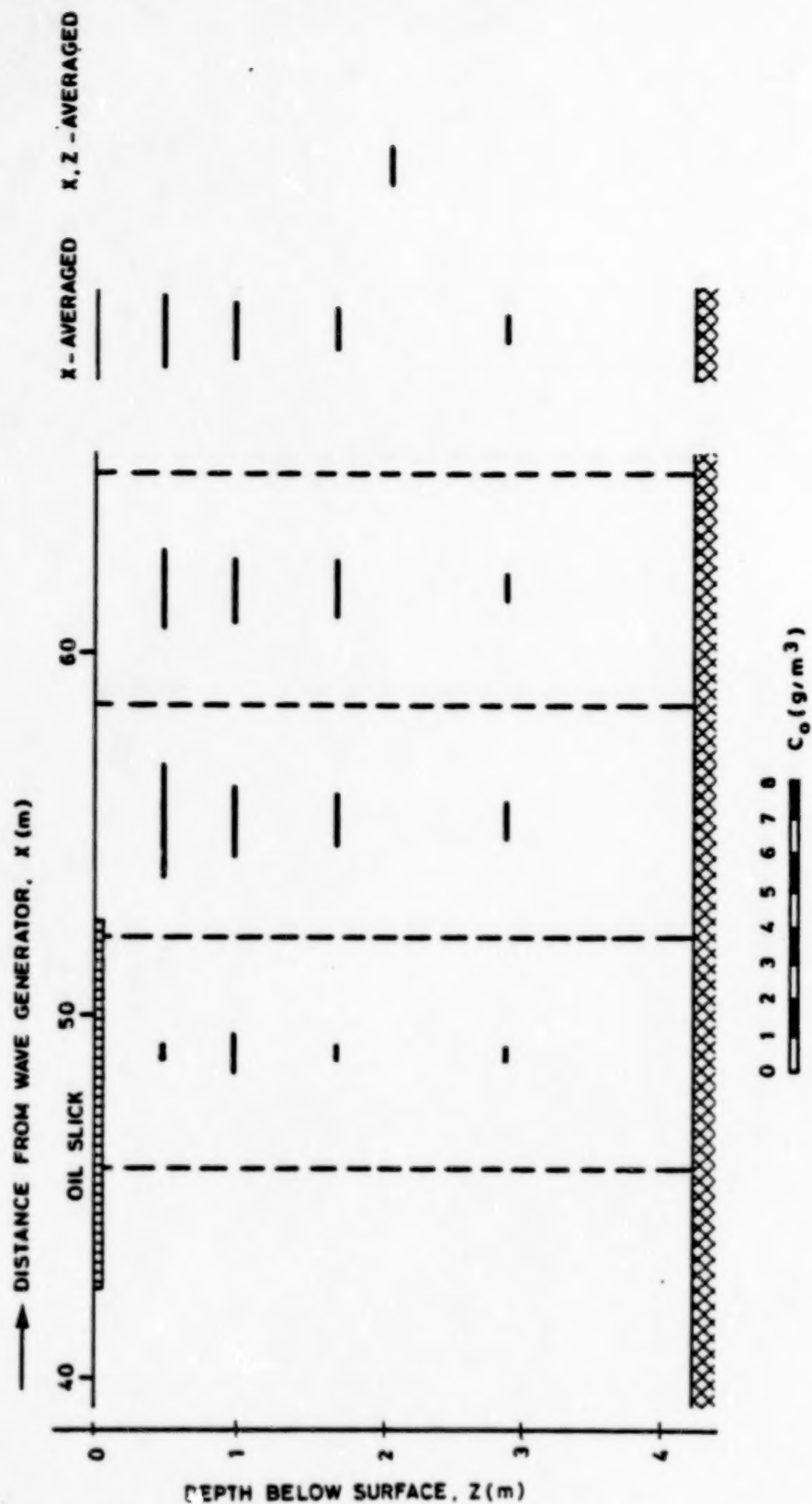


FIGURE VI.26 Experiment F2. Measured oil concentrations in the dispersed oil cloud at $t_m = 15$ minutes after the breaking wave

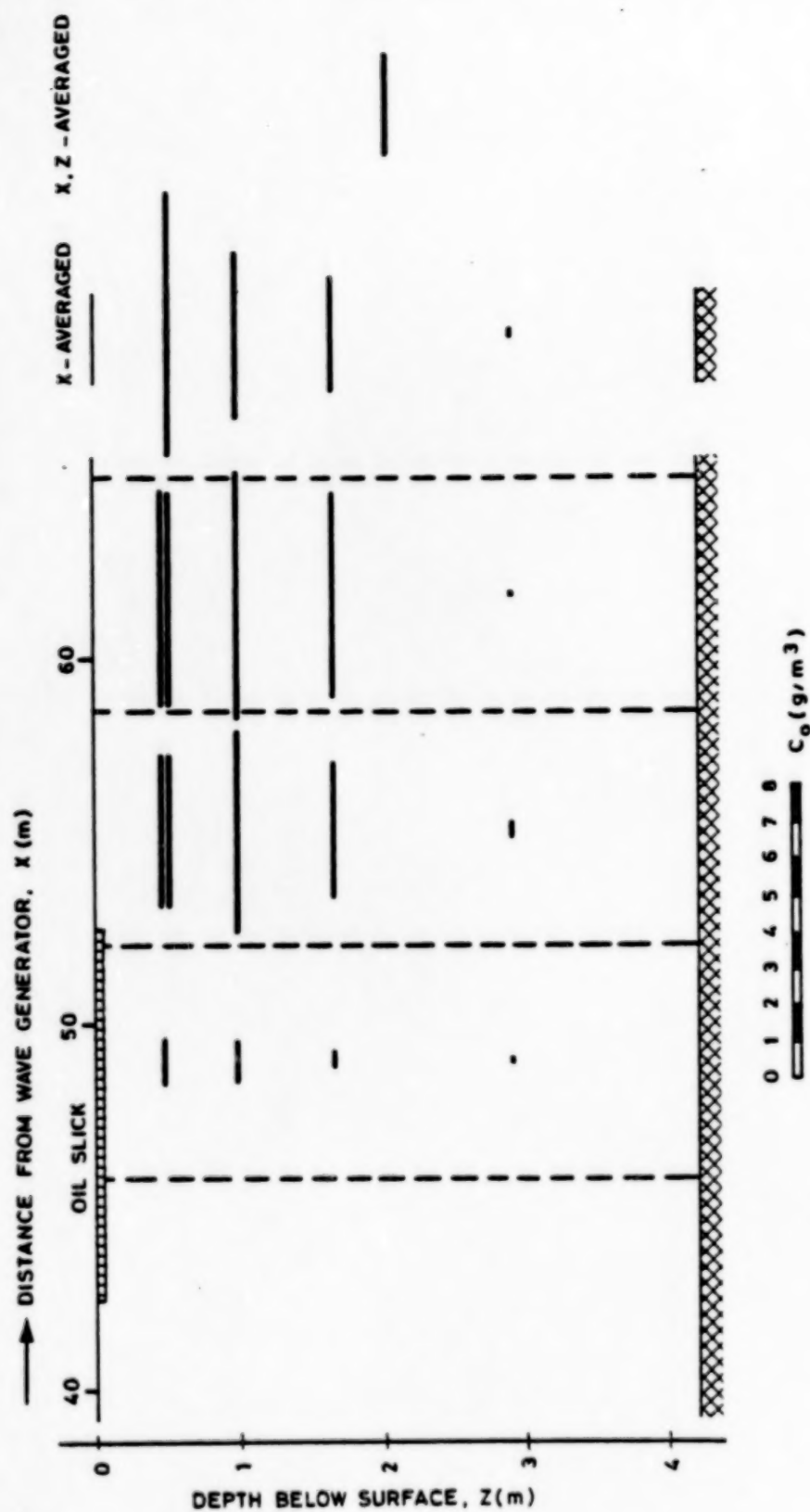


FIGURE VI. 27 Experiment F3. Measured oil concentrations in the dispersed oil cloud at $t_m = 15$ minutes after the breaking wave

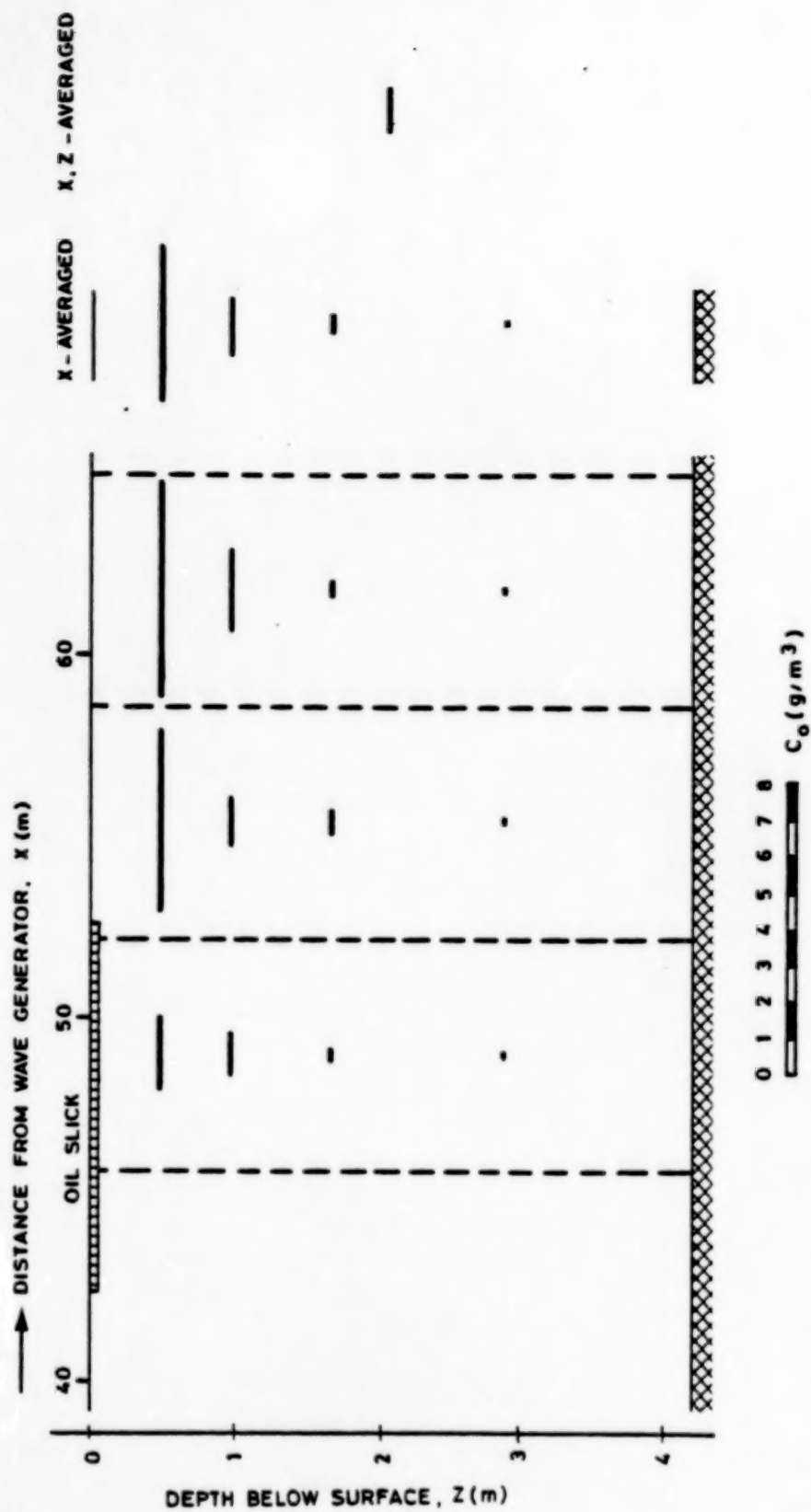


FIGURE VI. 28 Experiment F4. Measured oil concentrations in the dispersed oil cloud at $t_m = 15$ minutes after the breaking wave

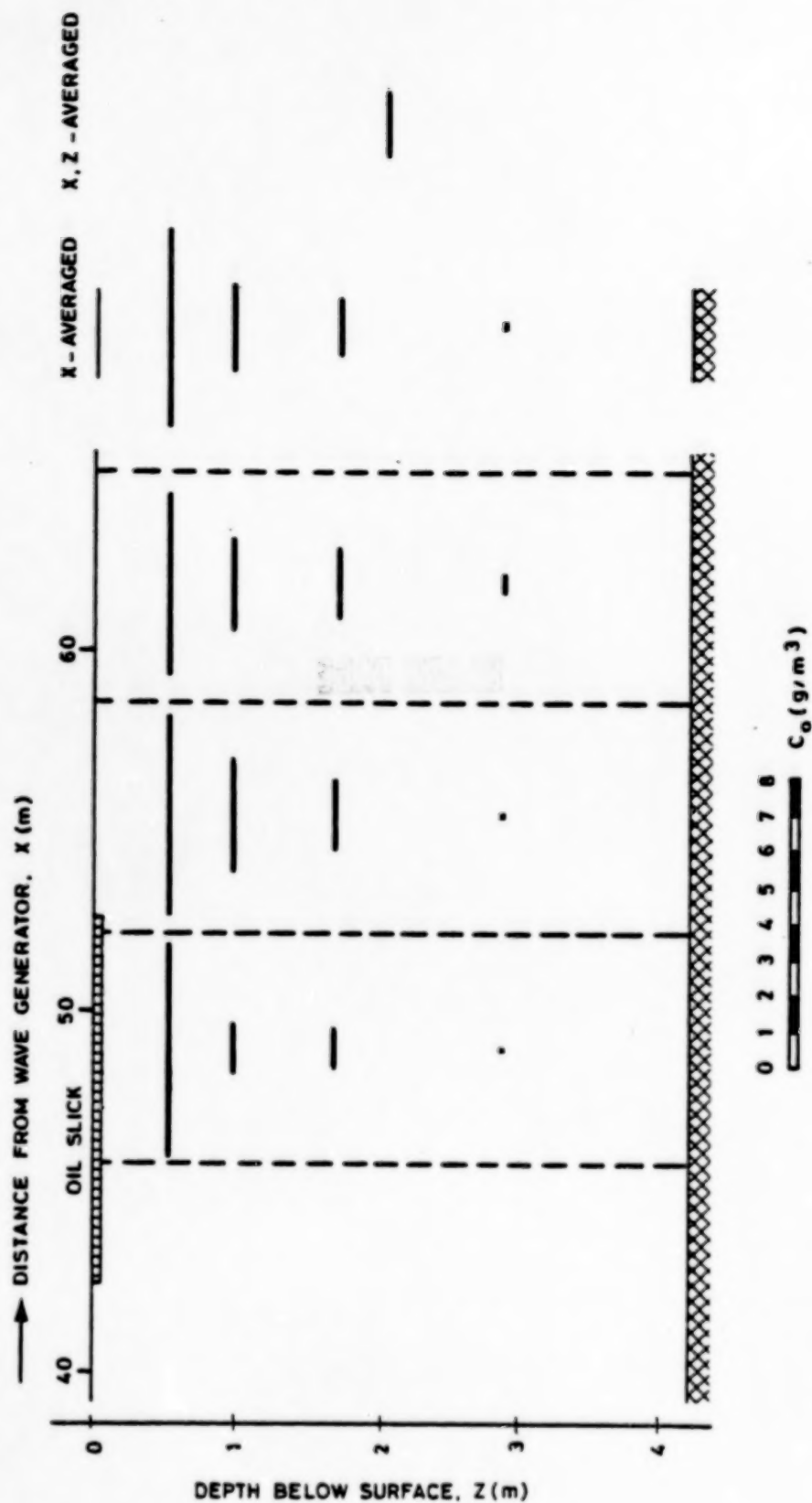


FIGURE VI. 29 Experiment F5. Measured oil concentrations in the dispersed oil cloud at $t_m = 15$ minutes after the breaking wave

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VII. INTEGRATION OF THE OIL DISPERSION EXPERIMENTS

Oil droplet break-up experiments in three different laboratory facilities were treated in the Sections III, V and VI. A short survey of the separate conclusions drawn from these experiments is given in Section VII.1. The Sections VII.2 to VII.6 contain the integration of the dispersion experiments leading to the final description of the dispersion of oil.

VII.1 Review of the Oil Dispersion Experiments

The following experiments on oil droplet break-up were discussed before:

- a) Grid column experiment on oil droplet break-up in a homogeneous turbulence field (Section III).

The measurements led to the following empirical relation between the oil droplet size, the oil viscosity ν_o , and the turbulent level expressed by the energy dissipation rate ϵ ($J/s\ m^3$):

$$d_{50} = c_1 \nu_o^{0.34} \epsilon^{-0.50} \quad (VII.1a)$$

$$d_{max} = c_2 \nu_o^{0.34} \epsilon^{-0.50} \quad (VII.1b)$$

This relation was valid in conditions with turbulence levels large enough so that the droplet break-up due to shear from the terminal velocity could be neglected. The proportionality constants c_1 and c_2 in Equation (VII.1) depend on the duration of the turbulence. The droplet sizes decreased with continuing turbulence until a steady state was obtained after about five minutes. Clearly the time to obtain a steady state is considerably longer than the duration of breaking-wave turbulence.

The steady state droplet size distributions arising from the break-up of submerged oil lumps and the break-up of surface films were found to be equal.

The effect of different types of oil, different weathering states and

different temperatures on the droplet size appeared to be expressed sufficiently by the viscosity in Equation (VII.1), within the range of applied parameters.

- b) Small-scale Oil Flume experiments on the break-up of a surface oil slick into droplets due to a breaking wave (Section V).

The measurements consisted of the determination of the oil concentration C_o and the oil droplet size distribution $d_o(f)$ as a function of the depth below the water surface, z , and the time t_m after the breaking-wave event. $d_o(f)$ was measured over a wide range, from $d_o = 3 \mu m$ to the size of the biggest droplets, on the order of magnitude of 1000 μm . The main results were:

- b1) the oil entrainment Q (per unit surface area per breaking wave event) increased with increasing breaking wave energy. (See, for instance, Figures V.24 and V.85)
- b2) the entrainment for different types of oil and weathering states is given on a relative scale by:

$$Q(PB_0) : Q(PB_{10}) : Q(Eko) = 1 : 0.6 : 2.2$$

- b3) all measured droplet size distributions fulfilled the relation:

$$N_u(d_o) \sim d_o^{-2.3} \quad (VII.2)$$

where $N_u(d_o)$ = number of droplets in a (small) unit size interval Δd around the droplet size d_o (e.g., interval $d_o - \frac{1}{2}\Delta d$, to $d_o + \frac{1}{2}\Delta d$, with Δd independent of d_o). Equation (VII.2) appeared independent of the oil type, weathering state, breaking-wave energy, temperature and oil layer thickness, as far as these parameters were varied in the experiments.

- b4) the maximum droplet size d_{max} observed in an experiment was dependent on the time t_m after the breaking event, apparently due to resurfacing of droplets. (Besides t_m , the resurfacing process depends on the oil-water density difference, the intrusion depth, and the vertical diffusion coefficient). No evidence was obtained for d_{max} -dependency on oil type and weathering state.

- b5) the entrainment Q was independent of the oil film thickness, h_o , within the applied range $h_o = 0.2$ to 1.2 mm.
- b6) no firm conclusions could yet be drawn about the effect of temperature on the oil entrainment.
- b7) the intrusion depth z_i of oil droplets due to the breaking wave is expressed by:

$$z_i = 1.5 (\pm 0.25) H_b \quad (\text{VII.3a})$$

and

$$z_i = 3.1 (\pm 0.7) h_{\text{bore}} \quad (\text{VII.3b})$$

with H_b = height of breaking wave

h_{bore} = maximum bore height of breaking wave

c.) Full-scale Delta Flume experiments on the break-up of a surface oil slick into droplets due to a breaking wave (Section VI).

A limited series of small-scale Oil Flume experiments was scaled up to "full scale" to check the validity of conclusions and extrapolations obtained from the experiments in the small flume and from experiments in the grid column. Conclusions from the full-scale experiments in the Delta flume must be related to the other oil break-up experiments and are discussed in the following sections.

VII.2 Oil Droplet Size Distribution

VII.2.1 Relative size distribution

All droplet size distributions in the small-scale Oil Flume experiments fulfilled the Equation (VII.2), $N_u(d_o) \sim d_o^{-2.3}$, independent of the applied oil type, weathering state, breaking-wave energy, temperature and oil layer thickness. This relation is confirmed by the five experiments in the large-scale Delta Flume where three different breaking waves and two types of oil were applied. Therefore, it is concluded that Equation (VII.2) was valid for the breaking-wave induced break-up of a surface oil slick in all conditions.

Almost all experiments in the grid column were carried out with droplet size distribution measurements by the LBPS which was capable of measurements in only a limited size range, $50 \mu\text{m} < d_o < 1000 \mu\text{m}$. A few tests were performed with the microscope-fluorescence apparatus, confirming the droplet size distribution according to Equation (VII.2) over the more extensive size range from $d_o = 3 \mu\text{m}$ (limit of routine measurement) to the biggest droplets present, $d_{\text{max}} = 1000 \mu\text{m}$. Apparently, the validity of Equation (VII.2) can be extended to the break-up of submerged oil parcels in a turbulent field.

The droplet distribution according to Equation VII.2 is compared with the droplet size distribution measurements in a wind-wave flume by Bouwmeester and Wallace (1986) (See Section II.2 and Figure II.5). The $N_u \sim d_o^{-2.3}$ curves were incorporated in Figure II.5 for $d_o \leq 250 \mu\text{m}$ and on a arbitrary N_u level. The curves with $N_u d_o = \text{constant}$ in the figures were suggested by Bouwmeester et al. as the droplet size distribution close to the water surface. The $N_u \sim d_o^{-2.3}$ curves are considerably different from the curves suggested by Bouwmeester et al., but the large spread in their measurements makes it difficult to judge the best correspondence of the curves with the measured data.

It is concluded from the grid column, Oil Flume and Delta Flume experiments that the oil droplet size distribution in a turbulent field is described by Equation (VII.2). The equation was valid for:

- a) different types of turbulence structure (due to breaking waves or other turbulence sources),
- b) break-up of surface oil films as well as break-up of submerged oil parcels,
- c) different types of oil and weathering states.

The equation is valid for droplet sizes from at least $d_o = 3 \mu\text{m}$ (limit of routine measurements) to the maximum droplet size present, d_{max} . The total volume V_{tot} for a droplet size distribution according to Equation (VII.2) can be expressed by:

$$V_{\text{tot}} = 1.45 V(d_{\text{max}}) \quad (\text{VII.4})$$

where: $V(d_{\text{max}})$ is the volume of oil in the size range $\frac{1}{2}d_{\text{max}}$ to d_{max} .
 V_{tot} is the volume of oil droplets in the size range from $d_0 = 0$ to $d_0 = d_{\text{max}}$, with the assumption that Equation (VII.2) is valid for droplets down to $d_0 = 0$.

VII.2.2 Maximum oil droplet size

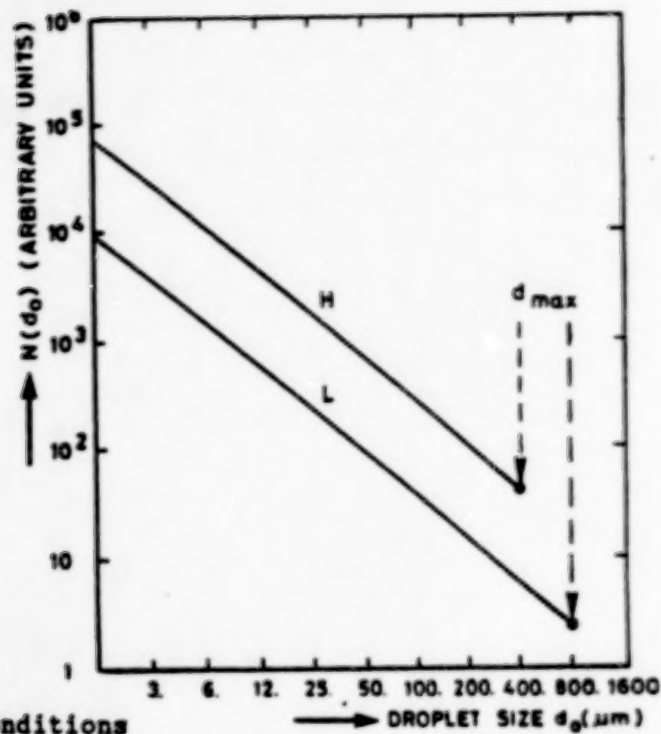
The value of the maximum droplet size d_{max} was measured in the grid column and in the flume experiments.

Grid column experiments with submerged oil

An important difference between the (deep) grid column and the (shallow) flume experiments is that in the former facility all oil droplets formed were taken into account in the droplet size distribution because surfacing of big droplets could generally be neglected. This means that all oil introduced in the column was included in $d_0(f)$. In the flume experiments only a small portion of the originally introduced oil film was still in suspension at the time of measurement, t_m , while this portion is also dependent on t_m due to resurfacing.

Equation VII.1b and Equation VII.2 describe the oil droplets in the grid column experiments in different turbulent conditions. The droplet sizes were smaller in experiments with higher energy dissipation rate e , but the total volume of oil was the same. Consequently, d_{max} decreased, as indicated also by Equation (VII.1b). d_{max} was also dependent on the duration of turbulence. Measurements with turbulence durations from $t_m = 5$ s to $t_m = 600$ s indicated that steady state values of d_{max} in high-turbulent conditions were obtained within five minutes.

Figure VII.1a shows schematically $N(d_0)$ versus d_0 curves for grid column conditions with turbulence level $e(H)$ (curve indicated by H) and turbulence level $e(L)$ (indicated by L). (In Figure VII.1a $e(H)/e(L) = 4$,



b) breaking wave in flume

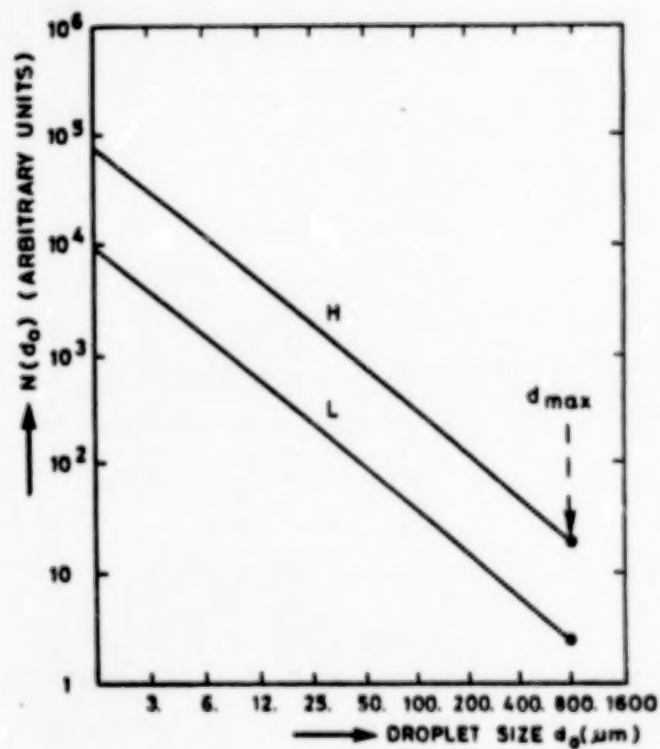


FIGURE VII.1 Schematic representation of oil droplet size distribution in relatively high (H) and low (L) turbulent ambience

leading to $d_{\max}(H)/d_{\max}(L) = 2$. The curves fulfil Equation VII.2). The relative $N(d_o)$ values are taken in such way that the total volume of oil in an experiment, V_{tot} , is equal for both curves. This means that the number of droplets in a size range, $N(d_o)$, in the grid column experiments is related to the energy dissipation rate ϵ according to $N(d_o) \sim V_{\text{tot}}/d_o^3$ with $d_o \sim \epsilon^{-0.5}$ and $V_{\text{tot}} = \text{constant}$. Therefore

$$N(d_o) \sim \epsilon^{1.5} \quad (\text{VII.5})$$

Flume experiments with surface oil film

In experiments with breaking waves, the entrained oil is generally only a small fraction of the total oil mass in the surface slick. Or, to put it in another way, all surface oil is submerged by the breaking wave, but the oil lumps and big oil droplets resurface almost immediately after the breaking event. The small-scale and large-scale flume experiments showed a decreasing $d_{\max}$ with increasing time t_m after the passage of the breaking wave. $d_{\max}$ appeared equal for small-scale and large-scale experiments if proper scaling of the resurfacing phenomena was employed (i.e., the length scaling factor $n_1 = 10$ means that the intrusion depth ratio equals 10 and therefore, the time of measurement t_m ratio equals 10 with respect to the resurfacing of droplets of the same size in both experiments). Finally, equal values for $d_{\max}$ were observed for experiments with different breaking wave conditions, except the differences that could be explained from different resurfacing (e.g., different intrusion depths due to the breaking waves).

It is concluded from the Oil Flume and Delta Flume experiments on the break-up of oil surface slicks by breaking waves that the maximum droplet size $d_{\max}$ found in the water mass for one type of oil, was independent of the break-up processes of the turbulent field, but was rather dependent on resurfacing parameters (e.g., intrusion depth z_1 , terminal velocity of the oil parcels W , diffusion coefficient ϵ_z , and time after the breaking wave event t_m ; see also the diffusion equation 2.1).

Table VII.1 Empirical depth of initial intrusion z_i (m)

Parameter	small scale				large scale		
	wave 2	wave 3	wave 5	wave 7	wave 2	wave 3	wave 5
H_b	0.23	0.24	0.15	0.10	1.90	1.80	1.40
$h_{bore} (-2 \bar{h}_{bore})$	0.12	0.12	0.08	0.04	0.80	0.70	0.50
z_i	0.40	0.325	0.20	0.15	3.50	2.00	2.00
z_i/H_b	1.74	1.35	1.33	1.50	1.84	1.11	1.43
$\overline{z_i/H_b}^{av.}$	← 1.48 →				← 1.46 →		
z_i/h_{bore}	3.33	2.70	2.50	3.75	4.38	2.86	4.00
$\overline{z_i/h_{bore}}^{av.}$	← 3.07 →				← 3.75 →		

It seemed plausible to assume that the number of droplets in a size interval, $N(d_o)$, due to oil break-up in a breaking wave turbulence field, is dependent on the turbulence level in a similar way as found in the grid column investigation with homogeneous turbulence conditions. Therefore, the following assumption was made:

$$N(d_o) \sim e_7^{1.5}$$

where e_7 is a characteristic energy of the breaking wave. This characteristic energy had to be defined and was indeed found as discussed in Section VII.3.

The schematic relations between $N(d_o)$ and d_o intervals are shown in Figure VII.1b for a relatively high-energy breaking wave (H) and a relatively low-energy breaking wave (L). The examples concern a characteristic energy ratio $e_7(H)/e_7(L) = 4$, whatever this characteristic energy may be. The values of d_{max} are equal for both breaking-wave conditions. The portions of the $N(d_o) - d_o$ curves for large droplets may deviate from the straight lines in Figure VII.1b, due to resurfacing of large droplets in the course of time. This was clearly shown in the Oil Flume measurements, Section V, and the Delta Flume experiments, Section VI. The resurfacing of large droplets depends, among other things, on the intrusion depth z_i of the oil droplets and, therefore, on the breaking wave characteristics.

VII.3 Oil Droplet Intrusion Depth

The measured values of the intrusion depth z_i for different breaking waves in the small-scale experiments (Table V.5) and the large-scale experiments (Table VI.5) are surveyed in Table VII.1 together with the measured values of the breaking wave height H_b and the maximum bore height of the breaking wave h_{bore} . The ratios z_i/H_b and z_i/h_{bore} are also given.

The small-scale and large-scale experiments are in good agreement as regards the linear relationship between z_i and H_b , and z_i and h_{bore} :

Small-scale experiments:

$$z_i = 1.5 H_b$$

$$z_i = 3.1 h_{bore}$$

Large-scale experiments:

$$z_i = 1.5 H_b$$

$$z_i = 3.75 h_{\text{bore}}$$

Averaging of the coefficients result in the general intrusion depth equation:

$$z_i = 1.5 H_b \quad (\text{VII } 6a)$$

$$z_i = 3.4 H_{\text{bore}} \quad (\text{VII } 6b)$$

Equation VII.6a is in good agreement with laboratory measurements of Nilsen et al. (1985) resulting in an intrusion depth of $1.5 H_b$ to $2.0 H_b$.

VII.4 Entrainment of Oil

One of the goals of the oil dispersion experiments was to relate the entrainment of surface oil to breaking wave characteristics. Indeed, the entrainment Q appeared strongly dependent on the energy dissipation of the breaking wave, with increasing Q for increasing breaking-wave energy.

Initially, the energy dissipation rate per volume, e (J/s m^3), was assumed to play an important role in the break-up of oil slicks. This parameter was varied in the homogeneous turbulence conditions of the grid column experiments. Equation VII.1 gives the relation between the average droplet size d_{50} and e in the turbulent field. Entrainment was not studied in the grid column experiments because the oil was almost always introduced below the water surface in the column.

The value e in the generated turbulence field was calculated from measured data for all applied breaking waves in the Oil Flume as well as in the Delta Flume. However, the data did not indicate a clear relationship between e and the total amount of dissipated energy (per unit width) D_b (J/s m), possibly because energy dissipated by different breaking waves could be spread over different lengths (i.e., wave-breaking over different distances), over different depths (i.e., different intrusion of the

turbulence field in the water mass), and the generated local turbulence could persist over different times. The empirical values of the entrainment Q for different breaking waves could not be related to the energy dissipation rate ϵ .

The proper relation between Q and characteristic breaking-wave energy parameters could be obtained from the following considerations:

- a) The grid column experiments demonstrated a decreasing droplet size with increasing turbulence energy dissipation rate per volume, ϵ (J/s m^3), and with increasing turbulence duration, t_{grid} . The time dependence occurred in any case for short times with $t_{\text{grid}} \leq 300$ s. Therefore, it was not unreasonable to suppose that the total energy dissipation per unit volume (J/m^3) was the important parameter for short-duration turbulent conditions, rather than the energy dissipation per unit volume per unit time, ϵ (J/s m^3) in the grid column experiments.
- b) It is plausible to assume that similar processes are responsible for both increasing oil entrainment with increasing breaking-wave energy in the flume experiments, and the decreasing droplet sizes with increasing turbulent energy in the grid column experiments. Therefore, the oil entrainment due to a (short-duration) breaking wave could be related to the energy dissipation rather than to the energy dissipation rate.
- c) Evidently, the break-up of submerged oil in the grid column experiments had to be related to the energy dissipation or the energy dissipation rate per volume. This does not mean that the break-up of a surface oil film by a breaking wave is also related to an energy level per unit volume, but it might very well be that an energy level per unit surface area was the important parameter because all dissipated breaking-wave energy passed through the oil surface film and hit the oil before spreading over a certain depth.

The relation between the entrainment Q and a characteristic energy parameter was found from the preceding considerations together with the following gross measured data:

- a) relative oil entrainment data for PB₀ oil and Ekofisk oil

- a) relative oil entrainment data for PB₀ oil and Ekofisk oil
- small-scale Oil Flume experiments with the waves 2, 3, 5 and 7:
 $Q(PB_0) : Q(Eko) = 1 : 2.2$ (See the Figures V.85 and V.86a).
 - large scale Delta Flume experiments with wave 2 and wave 5:
 $Q(PB_0) : Q(Eko) = 1 : 3$ (See Tables VI.3 and VI.5)
- b) surface-covered fraction:
- Oil Flume: $S_{cov}(PB_0) = S_{cov}(Eko) = 1$
 - Delta Flume: $S_{cov}(PB_0) = 0.25$, $S_{cov}(Eko) = 0.35$
- c) entrainment with different waves:
- Delta Flume, see Tables VI.3 and VI.5.
 Experiments with PB₀ oil resulted in the ratios
 $Q(\text{wave 2}) : Q(\text{wave 3}) : Q(\text{wave 5}) = 1.6 : 1.9 : 1$
 Experiments with Ekofisk oil resulted in the ratio
 $Q(\text{wave 2}) : Q(\text{wave 5}) = 1.5 : 1$
 - Oil Flume, see Figures V.24 and V.25^{*}
 Experiments with PB and Ekofisk oil resulted in the ratios:
 $Q(\text{wave 2}) : Q(\text{wave 3}) : Q(\text{wave 5}) = 2.3 : 1.8 : 1$
- d) oil layer thickness h_o . Oil Flume experiments resulted in the conclusion that the entrainment Q is independent of h_o .
- Note: The $Q(PB)/Q(Eko)$ ratios from Delta Flume and Oil Flume experiments must be regarded relative to the surface coverage fraction S_{cov} in the various experiments, and the conclusion that Q is independent of h_o . Q 's independence from h_o means that Q is linearly proportional to S_{cov} . Therefore, the $Q(PB_0)/Q(Eko)$ ratio in the Delta Flume (1:3) changes to 1 : 2.1 if the ratio is normalized to equal values of S_{cov} . This ratio must be compared with the Oil Flume ratio, see Section a, where $S_{cov} = 1$ for all experiments.

* The Figures V.24 and V.25 deal with the oil concentration in the dispersed oil cloud. Besides boundary effects at the beginning and end (in longitudinal direction in the flume) of the cloud, the depth-averaged oil concentrations are linearly related with Q rather than Q_{tot} .

- e) Entrainment at small scale and large scale. Similar (scaled) experiments were performed in the Oil Flume and in the Delta Flume with application of wave 2 and wave 5, and with Prudhoe Bay oil and Ekofisk oil. Delta flume values of Q are given in Table VI.5, and in principle, Oil Flume data of Q can be derived from the depth-averaged concentration data in the Figures V.24 and V.25. The comparison between the Oil Flume data and Delta Flume data of these values of Q is hampered by the fact that Q is strongly dependent on time (t_m), as discussed before in Section V.5. The time-dependence is caused by the resurfacing of big droplets in the course of time, and can be observed by comparing Figure V.24, $t_m = 40$ s, with Figure V.25, $t_m = 240$ s. (C_o versus time t_m is also shown in Figure II.2a from comparable previous experiments in the Oil Flume). The comparison of the time-dependent values of Q in the two flumes requires the consideration of the time scaling factor. This scaling factor is probably $n_{tm} = 10$ because the surfacing time of similar droplets is ten times longer if the intrusion depth in the Delta Flume is ten times greater, as it is. Consequently, the concentration measurements in the Delta Flume, at $t_m = 15$ minutes, must be compared with concentration measurements at $t_m = 1.5$ minutes in the Oil Flume. This could be performed by interpolation of the data in Figure V.24 ($t_m = 40$ s) and Figure V.25 ($t_m = 240$ s), making use of C_o versus t_m curves as in Figure II.2a.

A different method of comparing the entrainment in the flumes eliminates the uncertain time-dependent resurfacing process, and eliminates as well the differences in resurfacing due to the application of salt water in the Oil Flume and fresh water in the Delta Flume. This method compares the values of $N(d_o)$ for small droplet size classes where resurfacing is negligible. (See also Section V.5). The latter method was applied and resulted in the following ratio of the measured entrainment Q_m for Oil Flume and Delta Flume, averaged over the four comparable experiments (PB_0 + wave 2, PB_0 + wave 5, Ekofisk + wave 2, and Ekofisk + wave 5). It is noted that the average ratio obtained with the former method described appeared in reasonable agreement with this value:

$$\frac{Q_m}{S_{cov}}(\text{Oil Flume}) : \frac{Q_m}{S_{cov}}(\text{Delta Flume}) = 1 : 17$$

If the entrainment Q is normalized to conditions with $S_{cov} = 1$, then the following ratio is found:

$$Q(\text{Oil Flume}) : Q(\text{Delta Flume}) = 1 : 17$$

The consideration of the oil entrainment values, Q , in various breaking wave conditions and the related energy parameters resulted in a firm empirical relation between the entrainment Q and the dissipated breaking-wave energy per unit surface area D_{ba} (J/m^2). D_{ba} was derived from the measured integrated power spectrum or from the hydraulic jump analog. The values of D_{ba} in the relevant conditions are (see Table V.2):

$$\left. \begin{aligned} D_{ba}(\text{Oil Flume, wave 2}) &= 9 \text{ J/m}^2 \\ D_{ba}(\text{Oil Flume, wave 3}) &= 5 \text{ J/m}^2 \\ D_{ba}(\text{Oil Flume, wave 5}) &= 2 \text{ J/m}^2 \\ D_{ba}(\text{Oil Flume, wave 2}) / D_{ba}(\text{wave 5}) &= 4.5 \\ D_{ba}(\text{Oil Flume, wave 3}) / D_{ba}(\text{wave 5}) &= 2.5 \end{aligned} \right\} \begin{array}{l} \text{measurements from} \\ \text{power spectrum} \end{array}$$

$$\left. \begin{aligned} D_{ba}(\text{Oil Flume, wave 2}) / D_{ba}(\text{wave 5}) &= 3.0 \\ D_{ba}(\text{Oil Flume, wave 3}) / D_{ba}(\text{wave 5}) &= 3.5 \end{aligned} \right\} \begin{array}{l} \text{from hydraulic jump} \\ \text{analog} \end{array}$$

$$\left. \begin{aligned} D_{ba}(\text{Delta Flume, wave 2}) / D_{ba}(\text{wave 5}) &= 2.5 \\ D_{ba}(\text{Delta Flume, wave 3}) / D_{ba}(\text{wave 5}) &= 2.1 \end{aligned} \right\} \begin{array}{l} \text{from hydraulic jump} \\ \text{analog} \end{array}$$

$$D_{ba}(\text{Delta Flume}) / D_{ba}(\text{Oil Flume}) = 60 = \text{averaged values derived from hydraulic jump analog}$$

$$D_{ba}(\text{Delta Flume}) / D_{ba}(\text{Oil Flume}) = 100 = \text{theoretical value using scaling factors.}$$

D_{ba} values obtained from the hydraulic jump analog are given only on a relative scale because the value of α is unknown (see Section VI.3). The relative D_{ba} value were calculated by supposing equal value of α for the different conditions.

The D_{ba} values obtained by different methods give an indication of the accuracy of the methods in relation to others. The most reliable D_{ba} values were assumed to be obtained from the power spectrum for the Oil Flume D_{ba} and the theoretical scaling of the Oil Flume power spectrum data for the Delta Flume D_{ba} . It is noted that the relative D_{ba} values in the Delta Flume, obtained from the hydraulic jump analog, were very consistent with the scaled Oil Flume data. These "most reliable D_{ba} data" are summarized in Table VII.2.

Assume a relation between energy and oil entrainment in the flume experiments similar to the grid column experiments:

$$Q \sim e_7^{1.5}$$

with e_7 = the characteristic breaking-wave energy to be found. Trying $e_7 = D_{ba}^C$ leads to the following values of the exponent C:

$C = 0.37 \pm 0.01x$, from Oil Flume ratio $Q(\text{wave 2}) / Q(\text{wave 5}) = 2.3$, see section c, and D_{ba} ratio equals 4.5

$C = 0.21 \pm 0.01x$, from Delta Flume ratio $Q(\text{wave 2}) / Q(\text{wave 5}) = 1.6$, see section c, and D_{ba} ratio equals 4.5

$C = 0.41 \pm 0.003x$, from ratio $Q(\text{Delta Flume}) / Q(\text{Oil Flume}) = 17$, see section e, and D_{ba} ratio equals 100

$C = 0.45 \pm 0.01x$, from (few) experiments resulting in $Q(\text{wave 3}) / Q(\text{wave 5}) = 1.85$, see section c, and D_{ba} ratio equals 2.5.

The four calculations of the exponent C made use of Q ratios averaged over the relevant experiments. A certain error of x percent in Q leads to an error of 2x percent in the Q ratios, and this results in the errors in C as given above. It is very difficult to estimate the accuracy of the Q values. An (assumed) error in Q of 12 percent ($x=12$) or more would lead to a consistent set of exponents C, if a consistent set means that the calculated values of C, including the errors overlap in part.

Averaging the values of the exponent C with a weight factor according to the relative error results in

$$C = 0.38 \pm 0.04$$

Table VII.2 Most reliable values of D_{ba} (in J/m^2)

	wave 2	wave 3	wave 5
Oil Flume	9	5	2
Delta Flume	900	500	200

where the error in C is not obtained from the accuracy of the measurements of Q, but is the minimum error that could lead to equal values of the D_{ba} exponent for the four sets of experiments. The derived value of C leads to the following Q - D_{ba} relation:

$$Q \sim D_{ba}^{0.57 (\pm 0.06)} \quad (\text{VII.7})$$

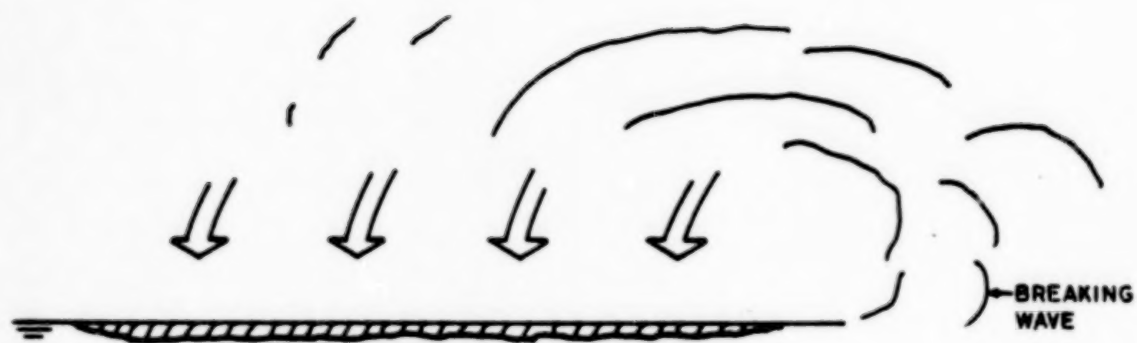
(Note: The empirical exponent $C = 0.38$ can be made plausible by the following description. A value $C = 0$ would indicate that the break-up of the surface slick depends on the energy dissipation per unit volume in the same way as the break-up of submerged oil in a turbulent field. The value $C = 1$ would indicate that the important parameter is the energy dissipation per unit surface area. A value of C with $0 < C < 1$ seems plausible from the assumption that the first break-up of the coherent surface layer is due to the turbulence passing through the surface area, and the continuing break-up of the oil parcels in the turbulence field is generated by the breaking wave energy in the upper water mass).

VII.5 Speculation on the Mechanism of Oil Break-up

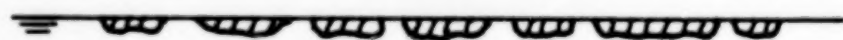
Two empirical conclusions on the break-up of coherent oil surface slicks are not immediately understood:

- a) the entrainment rate is independent of the layer thickness h_0
- b) the entrainment rate for Ekofisk oil is only a factor 2 larger than the entrainment rate of Prudhoe Bay oil, in spite of the considerably smaller oil droplets of Ekofisk oil in homogeneous turbulence conditions (grid column).

A simple, intuitive picture of the break-up of a surface oil layer is shown in Figure VII.2. A breaking wave approaches the oil slick and subsequently water plunges down on the slick (Figure VII.2a). The oil layer breaks up into pieces due to the forces of the falling water (Figure VII.2b). Further break-up of the oil lumps and oil droplets is caused by the turbulence generated by the breaking wave (Figure VII.2c). The initial break-up (VII.2b) will depend on the oil viscosity ν_o , surface



a)



b)



c)

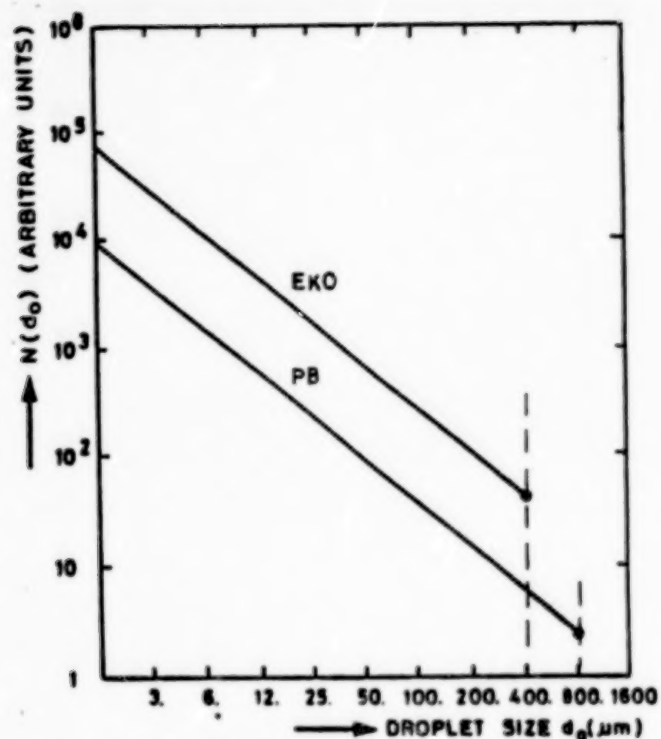
FIGURE VII. 2 Speculation on the break-up of surface oil films.
Fragmentation of the surface slick

tension σ_o and oil-water interfacial tension σ_{ow} , while smaller values of either v_o , σ_o or σ_{ow} will lead to smaller oil parcels. The continuing break-up (VII.2c) will depend on v_o and σ_{ow} , with smaller droplets for smaller values of v_o or σ_{ow} . Comparing Ekofisk oil and Prudhoe Bay oil, Ekofisk oil has lower values of v_o , σ_o , as well as σ_{ow} . The picture of Figure VII.2 would predict a break-up of Ekofisk oil into smaller droplets than with PB oil.

An intuitive relation between the entrainment rate of a surface oil layer and the droplet size of oil droplets in a homogeneous turbulence field can be drawn from considering the cascade of continuing break-up of oil lumps from big droplets into small droplets while always fulfilling the droplet size distribution according to Equation (VII.2). It is assumed that the presence of big droplets is not restricted by a lack of oil. This was true for the experiments on the break-up of oil slicks by breaking waves, where only a small portion of the surface slick was dispersed in the water column. This picture implies a relatively high entrainment rate by breaking waves for a type of oil where the oil droplets would be relatively small (i.e., easier to break-up) in a homogeneous turbulence field (grid column conditions). For instance, the break-up of Ekofisk and PB oil slicks results in oil droplet sizes in the grid column with $d_o(\text{Eko}) = 0.5 d_o(\text{PB})$, (see Figure VII.3a). The oil volume ratios $V(d_o, \text{Eko}) / V(d_o, \text{PB})$ in the smaller droplet size ranges will be equal in the grid column and in the flume. However, the flume curves extend to almost the same size for the largest droplets for both types of oil (ignoring the relatively small effect of faster resurfacing of Ekofisk droplets). (See also the comparable curves in Figure VII.1a,b for different turbulent energies instead of different oil types). The preceding oil break-up picture would lead to the entrainment ratio:

$$Q(\text{Eko}) / Q(\text{PB}) = \{ d_o(\text{Eko}) / d_o(\text{PB}) \}^{-3} = 8$$

However, the measurements show the quite different value $Q(\text{Eko}) / Q(\text{PB}) = 2.2$. A possible explanation for this difference is given below.



a) dispersion with limited submerged oil mass in grid column

b) dispersion with "unlimited" mass of surface oil in flume

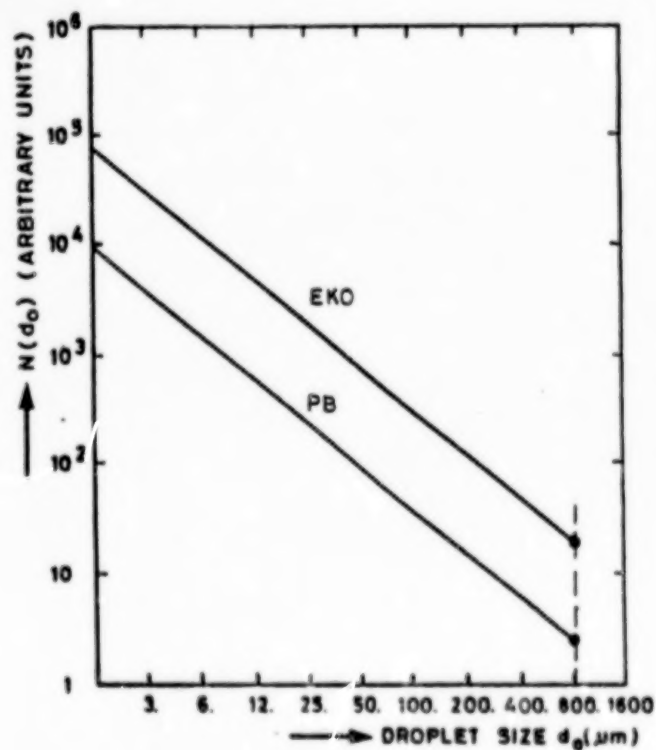


FIGURE VII. 3 Speculation on oil slick and droplet break-up.

$N(d_o) - d_o$ curves in flume and grid column experiments

Note: It is possible to explain the empirical conclusion that Q is independent of the surface layer thickness, based upon the supposed break-up cascade (see also Figure VII.2). The entrainment Q will be independent of h_o if the sizes of the largest droplets generated fulfil $d_o \sim h_o^{1/3}$ (e.g., doubling of the oil layer thickness leads to droplet sizes in the first cascade that are 1.26 times bigger). In that case, resurfacing of the indential large oil droplets in the experiments with different h_o , leads to equal values of Q . (The bigger droplets according to $d_o \sim h_o^{1/3}$ cancel the assumed proportionality of Q with the volume of oil. It is not unreasonable to assume from the image in Figure VII.2 that the initial break-up of a thick oil layer leads to bigger oil droplets or oil lumps than a thin oil layer).

The break-up picture in Figure VII.2 can explain the smaller droplets of Ekofisk oil as compared with Prudhoe Bay oil, but cannot explain satisfactorily the measured entrainment ratio. A quite different picture for surface oil break-up due to a breaking wave, is shown in Figure VII.4. The oil-water density difference $\Delta\rho$ and the oil spreading force play a role in this picture, while these parameters have considerably different values for Ekofisk and Prudhoe Bay oil (see Table A.1):

Ekofisk:	$\Delta\rho$	$= 200 \text{ kg/m}^3$
Prudhoe Bay:	$\Delta\rho$	$= 100 \text{ kg/m}^3$
Ekofisk:	σ_{net}	$= 0.01 \text{ N/m}$
Prudhoe Bay:	σ_{net}	$= 0$

in which the net surface tension force, σ_{net} , is defined by:

$$\sigma_{\text{net}} = \sigma_w - \sigma_o - \sigma_{ow}$$

Figure VII.4a1 shows a breaking wave approaching the edge of an oil slick. The oil at the edge is pushed up initially (Figure VII.4a2) and oil parcels are entrained by the breaking-wave eddies from the thickened slick edge (Figure VII.4a3). Now assume that Figure VII.4a shows the situation

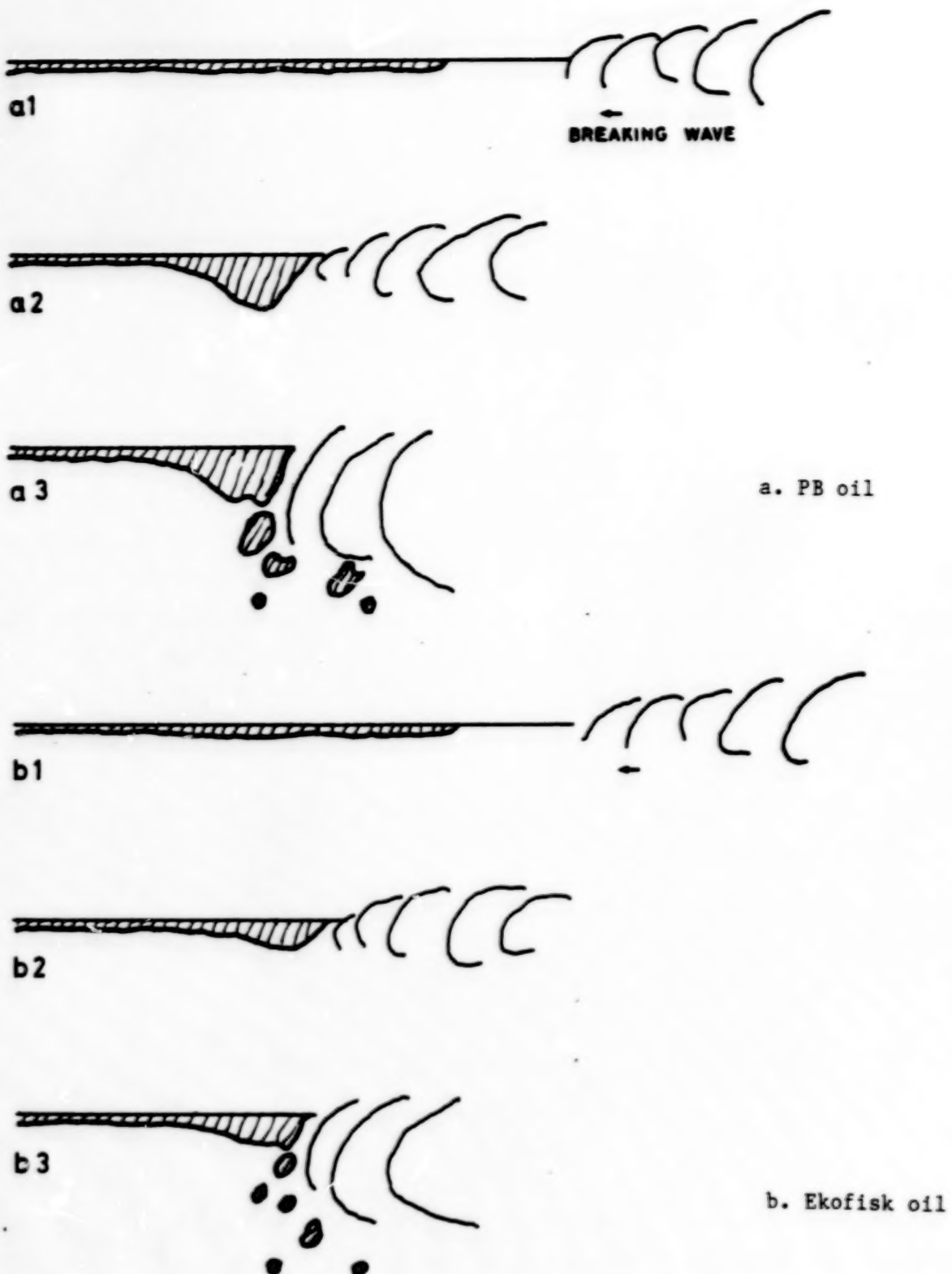


FIGURE VII. 4 Speculation on break-up of surface oil layers.
Stripping of the surface slick

for PB oil, and compare the situation for Ekofisk oil in Figure VII.4b. The initial conditions are assumed to be identical (Figures a1 and b1), but the pushing up of Ekofisk oil is less due to the counteraction of the net surface tension and the greater density difference (Figures a2 and b2). The breaking-wave eddy acts on a less massive edge and entrains less oil and smaller parcels (Figures a3 and b3). The smaller volume of the initially entrained Ekofisk oil offsets the relatively easy continuation of break-up into small droplets, and can explain the only modestly larger entrainment for Ekofisk oil (easy to break-up), compared with PB oil (more difficult to break up).

An indication of the validity of the break-up picture in Figure VII.4 was obtained from observation of two similar beakers with thin Ekofisk oil and Prudhoe Bay oil surface films. The beakers were placed on a shaking machine. (See Figure VII.5). The pushing-up of surface oil into strips was much more evident with PB than with Ekofisk oil. Moreover, the generated oil droplets were indeed larger for PB oil, while the dispersed oil volumes appeared to be of the same order of magnitude.

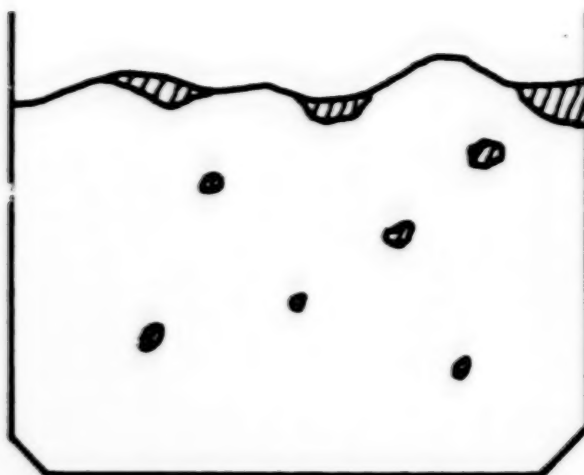
Both oil break-up pictures (Figure VII.2 and Figure VII.4) are suitable to explain qualitatively the independence of Q from the oil layer thickness h_o . The picture in Figure VII.4 explains better why dispersed oil droplet sizes d_o may be considerably bigger than the thickness of the surface layer h_o .

VII.6 Final Oil Entrainment Equation

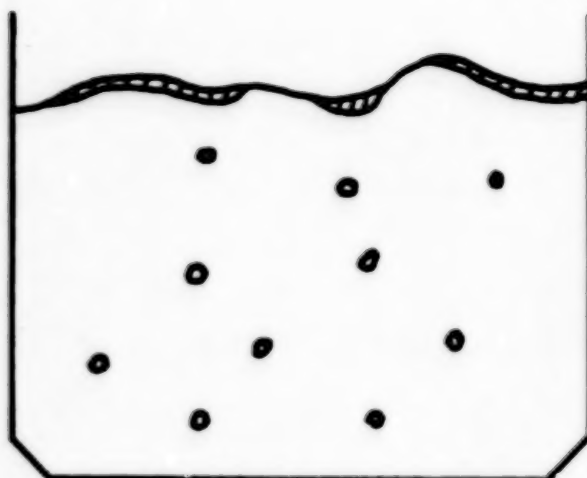
Equation (VII.7) is valid for all breaking wave experiments:

$$Q \sim D_{ba}^{0.57} \quad (VII.7)$$

For practical applications, the entrainment rate per unit area, Q_r (kg/s m^2), is more suitable to describe the dispersion of oil on a sea surface. The previous measurements showed the dependence of Q on the surface coverage fraction S_{cov} (with $0 \leq S_{cov} \leq 1$). All measurements were



a) PB OIL



b) EKOFISK OIL

FIGURE VII. 5 Speculation on break-up of surface oil. Observation in beakers.

performed with a single breaking wave event. Consequently, the entrainment rate Q_r for a sea surface can be described by:

$$Q_r = D_{ba}^{0.57} S_{cov} F_{wc} \quad (\text{VII.8})$$

with

- Q_r = oil entrainment rate ($\text{kg/m}^2\text{s}$)
- S_{cov} = fraction of sea surface covered by oil
- F_{wc} = fraction of sea surface hit by breaking waves per unit time (s^{-1})
- D_{ba} = dissipated breaking wave energy per unit surface area in the bore of the breaking wave (J/m^2)

In literature, analytical expressions are given for F_{wc} and D_{ba} as a function of wind speed and in different ocean conditions (surf zone, coastal zone, deep-water zone). The Interim Report (Delvigne et al., 1986) surveys the current knowledge in Sections 7.3 through 7.8.

The ultimate dispersion of oil depends on the initial intrusion of oil in the water mass due to the breaking wave, the turbulent vertical diffusion of the droplets in the water mass and the resurfacing of oil. The measurements have shown that the initially dispersed oil contained droplets of a wide size range, including oil parcels that quickly return to the water surface. Therefore, an applicable entrainment relation must describe the entrainment of oil droplets per size class. The measurements led to the relation between the number of dispersed oil droplets in a size class and the size itself given in Equation (VII.2), while the volume of an oil droplet is proportional to d_o^3 . Therefore, the entrainment per size class can be given by:

$$Q_r(d_o) = C(o) D_{ba}^{0.57} S_{cov} F_{wc} d_o^{0.7} \Delta d \quad (\text{VII.9})$$

where: $Q_r(d_o)$ = entrainment rate per unit area for oil droplets with droplet sizes in an interval Δd around d_o (e.g., the interval $d_o - \frac{1}{2}\Delta d$ to $d_o + \frac{1}{2}\Delta d$),

$C(o)$ = proportionality constant.

Remarks on the validity of Equation (VII.9):

- a) $Q_r(d_o)$ is considered to be the initially entrained volume of oil droplets (per unit area, per unit time) in a droplet size interval around d_o . These oil droplets are spread with a homogeneous concentration over the intrusion depth z_i due to the turbulence of the breaking wave. After this intrusion, the oil droplets are subjected to diffusing process in horizontal and vertical directions due to turbulence in the ambience (generated by wind, waves, currents, etc.) or rise to the water surface (resurfacing) due to the buoyancy of the droplets.
- b) Equation (VII.9) was derived from measurements on oil droplet sizes in the range from $3 \mu\text{m}$ to $1000 \mu\text{m}$. It is unknown how far Equation (VII.9) can be extrapolated to smaller droplet sizes, $d_o < 3 \mu\text{m}$, with the same constant $C(o)$. In any case, the volume of oil in the small d_o size ranges is very small compared with the larger size ranges (if these larger size ranges exist). This is expressed by the equation $V_t(d_o) = 1.45 V(d_o)$, where $V(d_o)$ is the volume of entrained oil in the size range $0.5 d_o$ to $1.0 d_o$ and $V_t(d_o)$ is the volume of oil for all droplets smaller than d_o (In this equation, the occurrence of droplets was assumed to continue to infinitely small droplets).
- c) In using Equation (VII.9) in mathematical models for description of oil dispersion, this equation can, in principle, be extrapolated to very large droplets. However, extrapolation to droplet sizes considerably larger than $d_o = 1000 \mu\text{m}$ generally does not make sense, because these large droplets are not kept in the water column by the residual turbulence in the sea against the buoyancy. The droplets resurface quickly in most cases after decay of the breaking-wave turbulence.

It is unknown how the maximum droplet size could be restricted by the surface layer thickness h_o . It was shown that $d_{\text{max}} > h_o$ for h_o in the order of 0.1 to 0.5 mm , but it is unlikely that d_{max} may exceed h_o by, say, a factor of ten.

- d) Equation (VII.9) reflects the independence of Q_r from the surface layer thickness h_o . This was tested for layer thicknesses $h_o = 0.2$ to 1.2 mm in the small-scale flume. It is reasonable to suppose that the h_o independence is also true for thicker layers, while limitations may occur for thin surface layers. As far as thin layers are concerned, it is evident that the amount of dispersed oil in a breaking wave cannot exceed the amount of oil in the oil layer. In the case of very thin oil layers, the suggestion is to use Equation (VII.9) for the small droplet sizes up to that value of d_o , where the amount of dispersed oil for a single breaking wave equals the oil layer volume.
- e) Oil entrainment measurements were performed for Ekofisk crude oil and Prudhoe Bay crude oil PB_0 and PB_{10} (fresh oil and weathered oil by evaporation for 10 days). Small-scale and large-scale measurements lead to the following values of the constants $C(o)$:

$$\begin{aligned} C(PB_0) &= 840 \\ C(PB_{10}) &= 510 \\ C(Eko) &= 1800 \end{aligned} \quad (VII.10)$$

These $C(o)$ values are the averaged values obtained by fitting the measured $N(d_o)$ values for small droplets (with negligible resurfacing) in the relevant Oil Flume and Delta Flume experiments with Equation (VII.9). Consequently the relative values of $C(o)$ for different types of oil are in agreement with the averaged relative entrainment values for equal values of S_{cov} , given in Section VII.1 and VII.3.

Application of the constants in Equation VII.9 is valid if the following definition of the parameters is taken into account:

$$\begin{aligned} Q_r(d_o) &= \text{entrained oil mass (kg) per unit area (m}^2\text{) per unit} \\ &\quad \text{time (s) for oil droplets in the (small) size range} \\ &\quad d_o - \frac{1}{2}\Delta d \text{ to } d_o + \frac{1}{2}\Delta d, \\ D_{ba} &= \text{breaking wave energy dissipation in J/m}^2 \\ S_{cov} &= \text{fraction of oil covered surface, } 0 \leq S_{cov} \leq 1 \end{aligned}$$

F_{wc} = fraction of surface area covered by breaking waves per unit time (in s^{-1})
 d_o, Ad = droplet sizes in metres (m).

f) Equation (VII.9) does not include the effect of temperature (T) and oil weathering on the entrainment rate.

Grid column experiments on the influence of temperature and weathering on the droplet size gave reliable results (Section III). The mean and maximum droplet sizes of dispersed submerged oil fulfilled the equation $d_o \sim \nu_o^{0.34}$ (See Figure III.65). The influence of temperature and weathering (and even oil type) on d_o could be described completely by the oil viscosity.

Because measurements with different oil weathering states (PB_0 , PB_3 and PB_{10}) and different temperatures ($16^\circ C$ and 9°) in the Oil Flume, Section V, were less accurate, it is not feasible to draw firm conclusions. Only rough indications can be given. The entrainment rate ratio $Q_r(PB_{10}) / Q_r(PB_0)$, averaged over three experiments with three different breaking waves, resulted in $Q_r(PB_{10}) / Q_r(PB_0) = 0.6$, see Figure V.85. The entrainment Q_r measured at different temperatures resulted in (see Figure V.86):

$$\begin{aligned} PB_0: \quad Q_r(2^\circ) : Q_r(8^\circ) : Q_r(15^\circ) &= 1 : 1.8 : 2.2 \\ Ekofisk: \quad Q_r(2^\circ) : Q_r(8^\circ) &= 1 : 1.7 \end{aligned} \quad (VII.11a)$$

It is suggested that the influence of weathering and temperature in Equation (VII.9) be allowed for a viscosity-dependent value of the constant $C(o)$, taking into account the following facts and suppositions:

- f1) $d_{50} \sim \nu_o^{0.34}$ for submerged oil (empirical fact)
- f2) different values of d_{50} for submerged oil break-up experiments lead to a surface slick break-up relation $N(d_o) \sim d_{50}^{-3} e^{1.5} \sim D_{ba}$ for the number of droplets with size d_o , in different breaking-wave (D_{ba}) conditions. (A similar supposition was applied in Figures VII.1a,b and VII.3a,b).

- f3) equal values of $d_{\max}$ are found for different temperatures and weathering states. (Similar supposition as applied in Figures VII.1b and VII.3b).
- f4) the preceding suppositions infer that Figure VII.4 is valid, with equal pushing-up of the oil for different temperatures and weathering states. This is not unreasonable because $\Delta\rho$ and σ_{net} change little with changing temperature and weathering.
- The preceding facts and suppositions together mean that:

$$Q_r = N(d_o) = d_{50}^{-3} v_o^{-1}$$

Based on application of Equation (VII.9), the following relationship holds:

$$C(o) = v_o^{-1} \quad (\text{VII.12})$$

for v_o varying by temperature or weathering.

Calculations of the relative entrainment ratio for PB₀ and Ekofisk oil with temperatures of 2°C, 8°C and 16°C, using Equation (VII.12) and the viscosities in Table (III.2), result in:

$$\begin{aligned} \text{PB}_0 &: Q_r(2^\circ) : Q_r(8^\circ) : Q_r(15^\circ) = 1 : 1.5 : 2.3 \\ \text{Ekofisk} &: Q_r(2^\circ) : Q_r(8^\circ) = 1 : 1.2 \end{aligned} \quad (\text{VII.11b})$$

This is in reasonable agreement with the empirical values in Equation (VII.11a).

Calculations for PB₁₀ and PB₀ resulted in $Q_r(\text{PB}_{10}) / Q_r(\text{PB}_0) = 0.42$. The measured value of 0.6 is in reasonable agreement with the calculation, but too few reliable measurements are available to conclude to the proposed relationship.

Note: The values of $C(o)$ in Equation (VII.1) were obtained from measurements at 12° (Delta Flume) and 15° (Oil Flume).

VII.7 Error Analysis and Applicability of Predictive Equations

This section contains a brief discussion of the probable error in the predictive equations derived, and the applicability of the equations in ocean conditions. In many cases, only a rough indication of the probable error and applicability is given, because the number of parameter values varied and the possibility to replicate individual experiments was too little to determine the statistical variability and the complete range of application.

The following equations are considered:

a) $N_u(d_o) \sim d_o^{-2.3}$ (VII.2)

This relationship was derived empirically from more than two-hundred N_u versus d_o graphs (see Figures V.31 through V.84 and Figures VI.10 through VI.24). The exponent -2.3 is the averaged value of all graphs. Significant differences in this relationship did not appear for measurements with different oil types and weathering states, different breaking waves, water temperatures, layer thicknesses, and measurements in the small and large flume. Therefore, Equation (VII.2) can be applied with high confidence in predictive models of oil behaviour in the ocean in all circumstances.

The spread of the exponent value in the measured graphs is given by -2.3 ± 1.0 . Assuming that the $N_u - d_o$ relationship is identical in all conditions, then the statistical error in the averaged value leads to the following relationship with probable error:

$$N_u(d_o) \sim d_o^{-2.3 (\pm 0.06)} \quad (\text{VII.2a})$$

b) $z_1 = 1.5 H_b$ (VII.3)

The relationship is in good agreement with other measurements in literature (see Section 7.3).

Table VII.1 shows the z_i versus H_b data from experiments in the small flume, and the averaged value over four experiments with different breaking waves:

$$z_i = (1.48 \pm 0.25) H_b \text{ (small flume)}$$

Three experiments with different waves in the large flume leads to:

$$z_i = (1.46 \pm 0.40) H_b \text{ (large flume)}$$

Apparently, the following relationship is valid over a wide range of breaking waves and can be applied in ocean conditions:

$$z_i = (1.50 \pm 0.35) H_b \quad (\text{VII.3a})$$

$$\text{c) } Q = D_{ba}^{0.57} (\pm 0.06) \quad (\text{VII.7})$$

The probable error in this relationship was already discussed in Section VII.4.

Equation (VII.7) was valid for experiments in the small flume, with wave height of about 0.2 m, as well as in the large flume with wave heights in the order of 2 m. Therefore, the relationship can be applied with reasonable confidence for the description of oil behaviour in ocean conditions. (In principle, a deviation could occur due to the different generation of breaking waves in the flume and in the ocean, in the former case by irregular waves from a waveboard, and wind-generated waves breaking in deep water or on a shallow sloping bottom in the latter case).

$$\text{d) } Q_r(d_o) = C(o) D_{ba}^{0.57} S_{cov} F_{wc} d_o^{0.7} \Delta d \quad (\text{VII.9})$$

The $Q - D_{ba}^{0.57}$ relationship is described in paragraph c. The linear relationship between Q and S_{cov} , and between Q and F_{wc} is evident. The relationship $Q - d_o^{0.7}$ is composed from $Q - d_o^{0.7}$ is composed from

$Q \sim d_o^{-2.3} d_o^3$ where the $d_o^{-2.3}$ proportionality is described in paragraph a, and $Q \sim d_o^3$ deals with the volume of an oil droplet.

Equation (VII.9) describes the entrainment of oil droplets in a (in principle infinitely) small droplet size range around the size d_o . The total amount of oil on a large interval $d_1 \rightarrow d_2$ is found by integration of Equation (VII.9) leading to

$$Q_r(d_1 \rightarrow d_2) = C(o) D_{ba}^{0.57} S_{cov} F_{wc} \cdot \frac{1}{1.7} (d_2^{1.7} - d_1^{1.7}) \quad (\text{VII.9a})$$

$$a) C(Eko) = 1800$$

$$C(PB_0) = 840 \quad (\text{VII.10})$$

$$C(PB_{10}) = 510$$

The $C(o)$ coefficients in Equation (VII.9) were derived by fitting the measured $N(d_o)$ values for small droplets (with negligible resurfacing) in the relevant experiments with Equation (VII.9) (See Section VII.6). The spread in the measured $N(d_o)$ values is large due to the inhomogeneous distribution of the oil concentration in the dispersed oil cloud (see, e.g., Figure V.19). If the values of $C(o)$ were derived by averaging the $N(d_o)$ values within the particular experiments (i.e., averaging over the samples 2A, 2B, 2C, 3A, 3B and 3C), then the spread of the $C(o)$ values for different experiments (with different breaking waves) with the same type of oil is about 50 percent. Four experiments were performed with Ekofisk and PB_0 oil (with waves 2, 3, 5 and 7) and three experiments with PB_{10} (waves 2, 3 and 5) in the small flume. This means that the error in $C(o)$ is of the order of 25 percent.

The coefficients for Ekofisk, PB_0 and PB_{10} oil in Equation (VII.10) did not lead to an obvious relationship between $C(o)$ and any characteristic oil parameter (e.g., viscosity, surface tension, interfacial tension). This means that the coefficients in Equation (VII.10) can be used with confidence in predictive models only for the indicated types of oil and weathering states. Other types of oil and weathering states (e.g., emulsified oil) need the empirical derivation of $C(o)$ from experiments with this particular type of oil, or possibly, an extensive series of experiments with different types of oil and weathering states may

result in a relationship between $C(o)$ and characteristic oil parameters that can be used for the prediction of $C(o)$ for other cases.

$$f) \quad d_{50}, d_{\max} \sim v_o^{0.34} e^{-0.50} \quad (\text{VII.1})$$

The relationship $d_o \sim v_o^{0.34}$ for submerged oil was derived from the empirical data shown in Figure III.65 (see also Figure ES.1a). The spread of the data indicates an error given by:

$$d_{50}, d_{\max} \sim v_o^{0.34} (\pm 0.05) \quad (\text{VII.1a})$$

The measurements suggest that Equation (VII.1a) is valid for all types of oil, weathering states and different temperatures, if the oil viscosity v_o is within the range from 8 to 220 cSt. Probably, Equation (VII.1a) can be extrapolated with some confidence to higher viscosities as long as the oil shows a newtonian behaviour. The relationship has little or no significance for non-newtonian oil types, as can be seen from the measurements on emulsified PB oil in Figure III.65, and the viscosity curve of PB_{em} in Figure A.27.

The relationship $d_o \sim e^{-0.50}$ for submerged oil was derived from data given in the Figures III.60, III.61 and III.64. (See also Figure ES.1b). The spread of the data indicates the following probable error:

$$d_{50}, d_{\max} \sim e^{-0.50} (\pm 0.1) \quad (\text{VII.1b})$$

Equation (VII.1) is supported by experiments in high-turbulence ambience with $e \geq 100 \text{ J/m}^3 \text{ s}$, and can be applied in predictive models for ocean conditions with the same lower limit of the turbulence level. The relationship in Equation (VII.1b) appeared independent of oil type, weathering state and temperature, and is probably valid for emulsified Prudhoe Bay oil as well, as shown in the experimental data in Figure III.64.

The break-up of submerged oil in low-turbulence water ($e \leq 100 \text{ J/m}^3 \text{ s}$) leads to smaller droplets than indicated by Equation (VII.1b), possibly because of the additional break-up of droplets due to the terminal

velocity. This tendency is shown in the measurements (Figures III.60, III.61 and ES.1b), but stationary-state measurements could not be performed because of the high rising velocities of the large oil droplets and the limited depth of the grid column. Reference is made to the literature as concerns the splitting of droplets in stagnant (non-turbulent) water due to the rising velocity (See the Interim Report, Delvigne et al. 1986, Section 4.7).

VII.8 Conclusions

The following empirical relations were found for the dispersion of oil due to breaking waves or other turbulence sources in the seawater:

- a) Break-up of submerged oil in the grid column, as well as break-up of surface oil slick in the small-scale Oil Flume and large-scale Delta flume demonstrate a general droplet size distribution given by:

$$N_u(d_o) \sim d_o^{-2.3} \quad (\text{VII.2})$$

where $N_u(d_o)$ = number of droplets in a (small) droplet size interval Δd around d_o (e.g., interval $d_o - \frac{1}{2} \Delta d$ to $d_o + \frac{1}{2} \Delta d$).
Equation (VII.2) is valid for oil droplets with $d_o < d_{\max}$.

- b1) In principle, $d_{\max}$ depends on the turbulence level and on oil-surfacing parameters. In deep water and high-turbulence conditions (simulated in many grid column experiments), surfacing is ignored and $d_{\max}$ is described by:

$$d_{\max} \sim e^{-0.5} \quad (\text{submerged oil}) \quad (\text{VII.1})$$

with e = turbulent energy dissipation rate per unit volume (J/s m^3).
 $d_{\max}$ depends also on the turbulence duration. $d_{\max}$ decreases with increasing time, while a steady state droplet size distribution is obtained within five minutes.

b2) In cases of surface oil dispersion due to breaking waves (Oil Flume and Delta Flume experiments), $d_{\max}$ depends on the following oil-surfacing parameters:

- $\Delta\rho$ = oil-water density difference,
- t_m = time after passage of a breaking wave,
- z_1 = intrusion depth due to wave breaking,

In field conditions, $d_{\max}$ depends on the residual vertical diffusion coefficient ϵ_z after decay of the breaking wave turbulence. Large droplets cannot be kept in the water column against the buoyancy and they resurface.

c) Oil entrainment by breaking waves is related to a characteristic breaking-wave energy by:

$$Q \sim D_{ba}^{0.57} \quad (\text{VII.7})$$

where Q = entrained oil mass per unit area per breaking event (kg/m^2)

D_{ba} = breaking-wave energy dissipation per unit area (J/m^2).

d) Oil entrainment by breaking waves is independent of the oil surface layer thickness h_o , within the experimentally applied h_o range $0.2 \leq h_o \leq 1.5$ mm.

e) The oil entrainment rate per size class $Q_r(d_o)$ is empirically described by:

$$Q_r(d_o) = C(o) D_{ba}^{0.57} S_{cov} F_{wc} d_o^{0.7} \Delta d \quad (\text{VII.9})$$

with

$Q_r(d_o)$ = mass of entrained oil droplets per unit surface area per unit time, for droplets in the (small) size interval Δd around d_o , (interval $d_o - \frac{1}{2}\Delta d$ to $d_o + \frac{1}{2}\Delta d$). (Q_r in $\text{kg/m}^2\text{s}$),

S_{cov} = fraction of sea surface covered by oil,

- F_{wc} = fraction of sea surface hit by breaking waves (white-caps) per unit time (s^{-1}),
- $C(o)$ = proportionality constant, variable for different oil types, weathering states and temperatures.

Empirical values of $C(o)$ are given in the Equations VII.10 for PB_0 , PB_{10} and Ekofisk oil. These values were derived from experiments at a temperature of about $13^\circ C$. The influence of the temperature on Q_r is taken into account, as far as could be derived from the experiments, by the relation $C(o) \sim \nu_o^{-1}$, where ν_o = oil viscosity varying by temperature.

Equation (VII.9) describes the initial entrainment of oil by a breaking wave (at $t_m = 0$). After the breaking event, the droplets are exposed to diffusion and resurfacing processes.

- f) The oil concentration and the oil droplet size distribution are homogeneous over the intrusion depth of the oil in the water mass z_1 , due to breaking waves. In the course of time, inhomogeneities arise due to resurfacing and diffusion processes.
- g) Breaking waves cause an intrusion depth of surface oil into the water mass, z_1 . The intrusion depth z_1 is linearly proportional with H_b = wave height of breaking wave, and h_{bore} = maximum bore height of breaking wave, by the relationships:

$$z_1 = 1.5 H_b \quad (VII.6a)$$

$$z_1 = 3.4 h_{bore} \quad (VII.6b)$$

The entrainment Q (kg/m^2) is defined as the dispersed oil mass in the water column per unit surface area per breaking event. Q depends strongly on the time after the passage of the breaking wave due to resurfacing of big droplets. Therefore, the following description of Q and droplet size distribution $d_o(f)$ is pursued as regards the dispersion of an oil surface film:

- a) The absolute $d_o(f)$ distribution is equal for all depths z within the intrusion depth z_1 for small droplet size classes not (yet) disturbed by resurfacing of droplets.
- b) The relative $d_o(f)$ distribution for small classes is given by Equation (VII.2). Initially, immediately after the breaking event, Equation (VII.2) is assumed to be valid up to infinitely large droplets.
- c) Absolute values of $N(d_o)$ are required for one or more (small) droplet size classes fulfill the homogeneity described in paragraph a.
- d) The maximum droplet size d_{max} at a given time t_m and at given depth z_o must be derived from measurements, or from calculations on the vertical diffusion of the buoyant droplets in the droplet cloud. All droplets smaller than d_{max} fulfil the conditions in paragraphs a and b for $t \leq t_m$ and $z \leq z_o$.

In other words, dispersion of oil due to a breaking wave is described by the following empirical parameters:

- a) intrusion depth z_1 ,
- b) relative droplet size distribution $d_o(f)$ according to Equation (VII.2),
- c) concentration and distribution for small droplets are equal for all depths z withing z_1 ,
- d) absolute values of $N(d_o)$ for at least one (small) size class,
- e) empirical and/or calculated data on maximum droplet size d_{max} .

The oil entrainment Q , due to breaking waves, appeared independent of the oil surface layer thickness h_o , within the applied values $h_o = 0.2$ to 1.2 mm. The maximum droplet size d_{max} may be considerable larger than h_o . No empirical data are available for very thin oil surface films where Q is restricted to the volume of the surface slick. It is suggested that one assume oil droplet dispersion according to the empirical relations found for the smallest size class until the size class where the entrainment oil mass per breaking event Q equals the surface slick volume. Actually, this principle can be applied for all film thicknesses.

For large thicknesses, the large droplets considered in this way resurface quickly.

VIII. DISCUSSION ON DISPERSION AND DIFFUSION OF OIL DROPLETS AND OILED PARTICLES

The present laboratory experiments were conducted in order to provide mathematical models on oil dispersion with empirical data. The mathematical models must describe the transport of spilt oil taking into account the following conditions:

- a) Oceanographic conditions : deep-sea, coastal waters, surf zone
: water temperature, water salinity,
SPM concentration
- b) Meteorological conditions : calm to stormy wind
- c) Oil spillage : surface, subsurface
- d) Oil characteristics : type of oil, weathering state, oil volume
- e) SPM characteristics : SPM type, particle distribution.

In general, a comprehensive consideration of the oceanographic and meteorological conditions must result in the model description of the tidal currents, wind-driven currents and the wind-driven waves, including the turbulence generated by the currents and (breaking) waves. The currents and turbulence in the seawater are responsible for the following processes as regards the spilt oil parcels:

- a) transport processes. The oil parcels and oil-SPM agglomerates move as a result of the currents, turbulence (diffusion) and buoyancy (related to fall or rise velocity in quite conditions).
- b) oil break-up processes. Surface oil films are broken-up by breaking waves* and dispersed into the water column by breaking wave tur

* It is not well understood whether breaking waves are necessary for oil film break-up. Some field investigations indicate dispersed oil droplets in the absence of breaking waves. However, this cannot be reproduced in (small-scale) laboratory models. The present study assumes that oil film break-up is due only to breaking waves.

bulence. Submerged oil parcels are broken-up by turbulence in the seawater.

- c) oil-SPM interaction processes. Collisions between oil droplets and SPM are (partly) due to turbulence.

Some of the processes in the mathematical models are well understood to a certain degree and quantitative data can be obtained from the literature, especially as regards the currents and turbulence structure. The present study provides experimental data with respect to the following processes:

- a) Break-up of submerged oil parcels in a turbulent ambience. The resulting oil droplet size distribution is given as a function of the turbulence level, the latter characterized by the energy dissipation rate per unit volume. Data are available for different types of oil, weathering states, different temperatures and turbulence duration.
- b) Breaking wave induced break-up of surface oil films, expressed in terms of entrainment of oil (volume of dispersed oil mass relative to surface slick mass), droplet size distribution of the oil broken-up by the turbulence of the breaking wave, and intrusion depth in the water column due to breaking wave turbulence.

The intrusion depth z_1 is given as a function of the bore height of the breaking wave. z_1 appeared independent of other parameters.

Oil entrainment Q and droplet size distribution $d_o(f)$ are given as a function of the dissipated energy per unit surface area in the bore of the breaking wave. $d_o(f)$ depends also on the oil type, weathering state and temperature; data are available and/or relationships are given for different values of these parameters. The dependence of Q on the oil film thickness, h_o , surface oil coverage fraction S_{cov} , oil type, weathering state and temperature is given by available data for different values of these parameters.

- c) Oil-SPM interaction data are not available in terms of quantitative data that could be related to actual sea conditions. The following results of the experiments conducted must be considered as mainly

qualitative information about the important parameters involved in the interaction process:

- c1 Oil-SPM interaction phenomena ranged from "oil droplets coated with SPM particles", to "oil droplets incorporated in SPM flocs". The buoyant, neutral or negatively-buoyant behaviour of an agglomerate depends on the oil-SPM ratio in the agglomerate.
- c2 The oil in oiled sediment consisted apparently of discrete droplets. The droplets observed in negatively-buoyant agglomerates were always in the size range $1 \mu\text{m} < d_o < 60 \mu\text{m}$, not significantly variable in experiments with different oil types, SPM types and turbulence levels.
- c3 A steady-state in the oil-SPM interaction experiments was obtained within 20 minutes with kaolinite SPM (organic carbon content OCC = 0), but was not obtained within three hours (= maximum duration of the experiments) with Waddensea SPM (OCC = 7 percent).
- c4 The oil content in the sediment was linearly proportional to the applied oil volume. The oil content was less in conditions with low concentrations of oil and SPM where, apparently, the low particle collision probability restricted the interaction.
- c5 Increasing turbulence level led to increasing oil/silt (o/s) ratio in the sediment.
- c6 The ranking of oil for oil adsorption on silt depends on the type of silt.
- c7 The weathered PB_3 oil was more adsorbed by SPM than the unweathered PB_0 oil.
- c8 Oil adsorption by Waddensea silt was considerably more dependent on variables (e.g., type of oil, turbulence level) than the oil-kaolinite interaction.

Consequently, the use of data given in this study in mathematical models requires the knowledge of the following parameters:

- a) turbulence profile in the water column in terms of energy dissipation rate per unit volume, ϵ (due to tidal currents and wind-driven currents)
- b) statistical properties of breaking waves (average area covered by

breaking waves per unit time, energy dissipation per unit surface area, bore height)

Moreover, further calculations on the transport of oil requires:

- c) diffusion coefficient profile ϵ in the water column (due to tidal currents and wind-driven currents).
- d) current velocity profiles (tidal currents, wind-driven currents and wave-induced currents).

These parameters in given hydrometeorological conditions must be obtained from the current knowledge in literature. A survey of the current knowledge is given in the Interim Report (1986) (See also Section II of the present study).

The stability and vertical diffusion of small oil droplets and the resurfacing of large droplets in the residual turbulence conditions of the ambient flow after the breaking wave event can be calculated with the diffusion equation:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z} \left(\epsilon_z \frac{\partial c}{\partial z} \right) + W(d_o) \frac{\partial c}{\partial z} \quad (\text{VIII.1})$$

where c = $c(d_o)$, oil concentration per droplet size class,
 ϵ_z = vertical diffusion coefficient,
 $W(d_o)$ = terminal velocity of oil droplet with size d_o .

The initial conditions of Equation (VIII.1) are the conditions shortly after the passage of the breaking wave as given in Section VII.8 with respect to the intrusion depth, droplet size distribution and homogeneity within the intrusion depth.

The data and relationships given in this study are, of course, only valid in the range of parameter values applied. It is expected that this is no serious limitation as far as the range of applied temperatures, breaking wave energies and submerged turbulence conditions are concerned. If the present study should be extended to a more comprehensive range of the parameters it would be wise to include more types of oil especially the high-viscosity oils and oil emulsions. This is emphasized by the observation of rapid emulsification in the small-scale as well as in the large-scale flume experiments, especially with Prudhoe Bay oil.

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APPENDIX A. LABORATORY METHODOLOGY AND QUALITY ASSURANCE PROCEDURE

A.1 Laboratory Test Facilities

A.1.1. Grid Column

Two series of experiments were performed in the grid column:

- a) experiments on the break-up of oil droplets in a turbulent field, see Section III.
- b) experiments on the interaction of oil droplets and SPM in a turbulent field, see Section IV.

The facility is shown schematically in Figure A.1. The height of the column is 4.25 m, and the internal diameter of the transparent perspex tube is 0.30 m. Inlets and/or outlets are situated at eleven locations. Submerged introduction of oil took place through one of the inlets near the bottom, Figure A.2 shows a photograph of the lower section of the column with the oil inlet system. In some experiments, the introduction of oil took place by putting an oil layer on the free water surface. The withdrawal of samples took place generally near the middle of the column.

Turbulence in the column is generated by an oscillating grid system, consisting of grid sections mounted on an axis over the whole length of the column, see Figure A.3a. The turbulence level depends on the shape of the grid, and the amplitude and the frequency of oscillations. The shape of a grid section is shown in Figure A.3b, the mesh size is 0.075 m, and the distance between the sections is also 0.075 m. The amplitude was fixed in the experiments on 0.075 m, while the frequency was varied from 0 to 4 s^{-1} . Rouse [1938] and Dobbins [1944] have shown that a vertical oscillating grid in a column generates a homogeneous turbulence field. The vertical diffusion coefficient ϵ_z in the turbulence field can be expressed by:

$$\epsilon_z = C f_{\text{grid}} A_{\text{grid}}$$

where f_{grid} = grid frequency

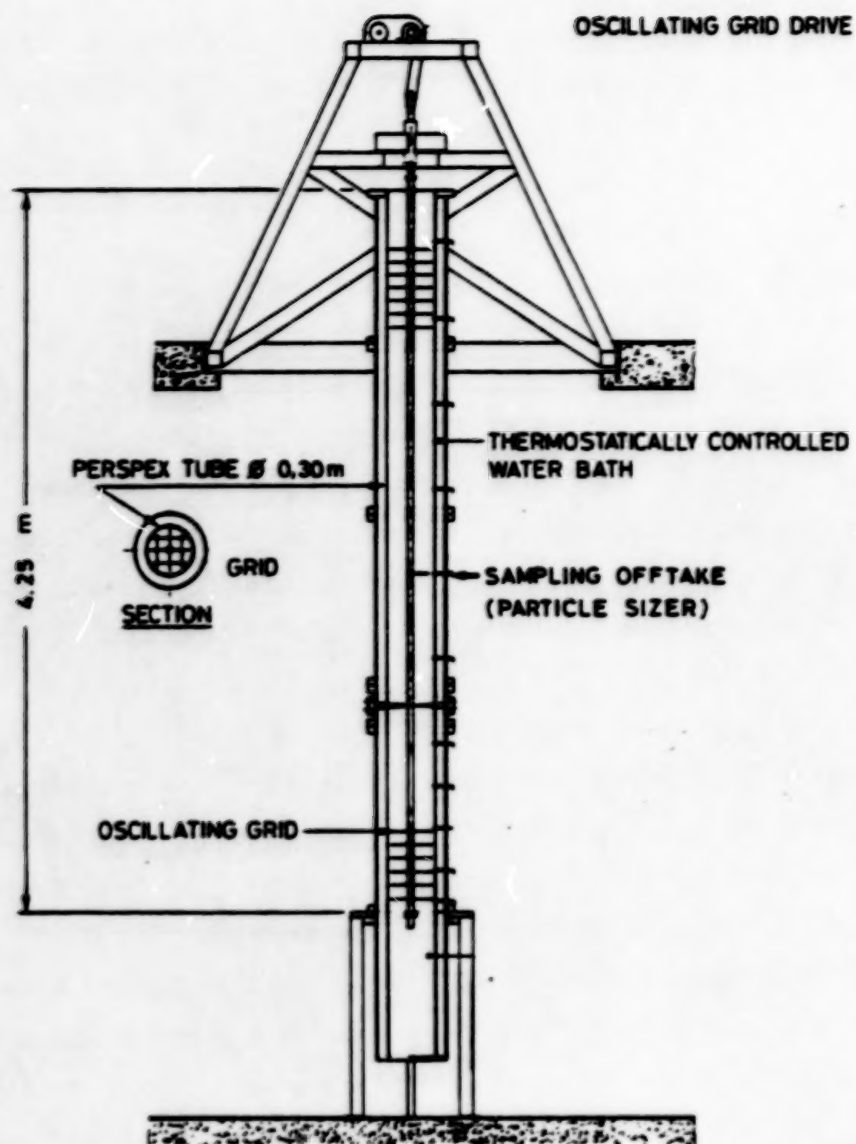


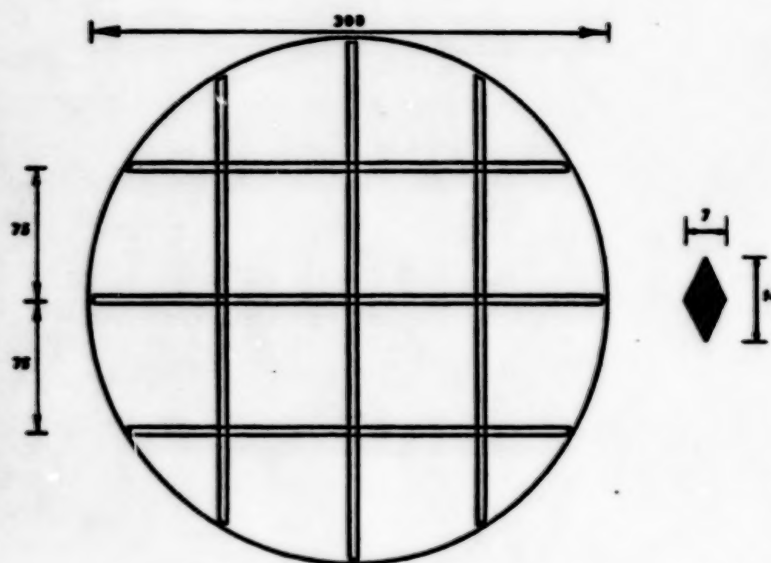
FIGURE A.1 Schematic grid column



FIGURE A.2 Grid column with oil inlet



a) View on grid in column



b) Cross sections of grid and grid rod (all measures in mm)

FIGURE A.3 Turbulence grid in the column

A_{grid} = grid amplitude
 C = constant

Rouse [1938] has measured the value $C = 0.2$ with a grid similar to that used for this study. It is supposed that the same value is valid for the present column. Figure A.4 shows the relation between c_z and f'_{grid} with $A_{\text{grid}} = 0.075$ m. The relation has been verified experimentally by measurements on the diffusion of fine sand in the column.

The energy dissipation in the column can be calculated in the following way. The force F on a grid section due to the water resistance is expressed by:

$$F = C_D A \frac{1}{2} \rho_w u_{\text{grid}}^2 \quad (\text{A.1})$$

with: C_D = drag coefficient
 A = grid surface perpendicular to oscillation direction
 u_{grid} = grid velocity = $\omega A_{\text{grid}} \cos \omega t$ (ω = angular velocity)

Equation (A.1) leads, for the present grid, to the following expression, if $C_D = 1.0$ is assumed:

$$F = 6.36 A_{\text{grid}}^2 \omega^2 \cos^2 \omega t$$

The supplied energy E per grid section and per unit time (s) is:

$$E = \frac{1}{2\pi} \int_0^{2\pi} F A_{\text{grid}} \omega \cos \omega t d(\omega t) = 2.7 A_{\text{grid}}^3 \omega^3$$

The energy dissipation rate e per unit volume (for 13.3 grid sections per meter) is:

$$e = 530 A_{\text{grid}}^3 \omega^3$$

The amplitude $A_{\text{grid}} = 0.075$ was applied in the experiments. Then:

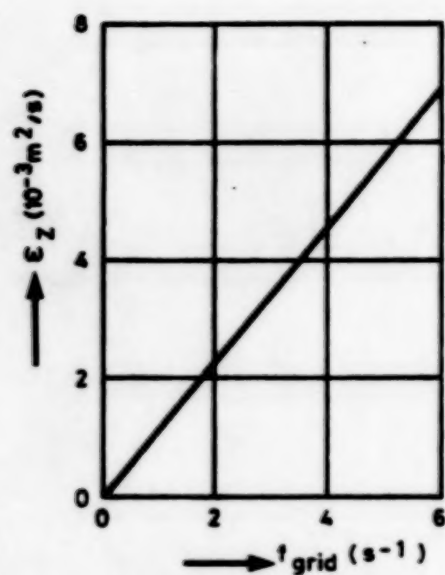


FIGURE A.4 Vertical diffusion coefficient ϵ_z versus grid oscillation frequency in the grid column

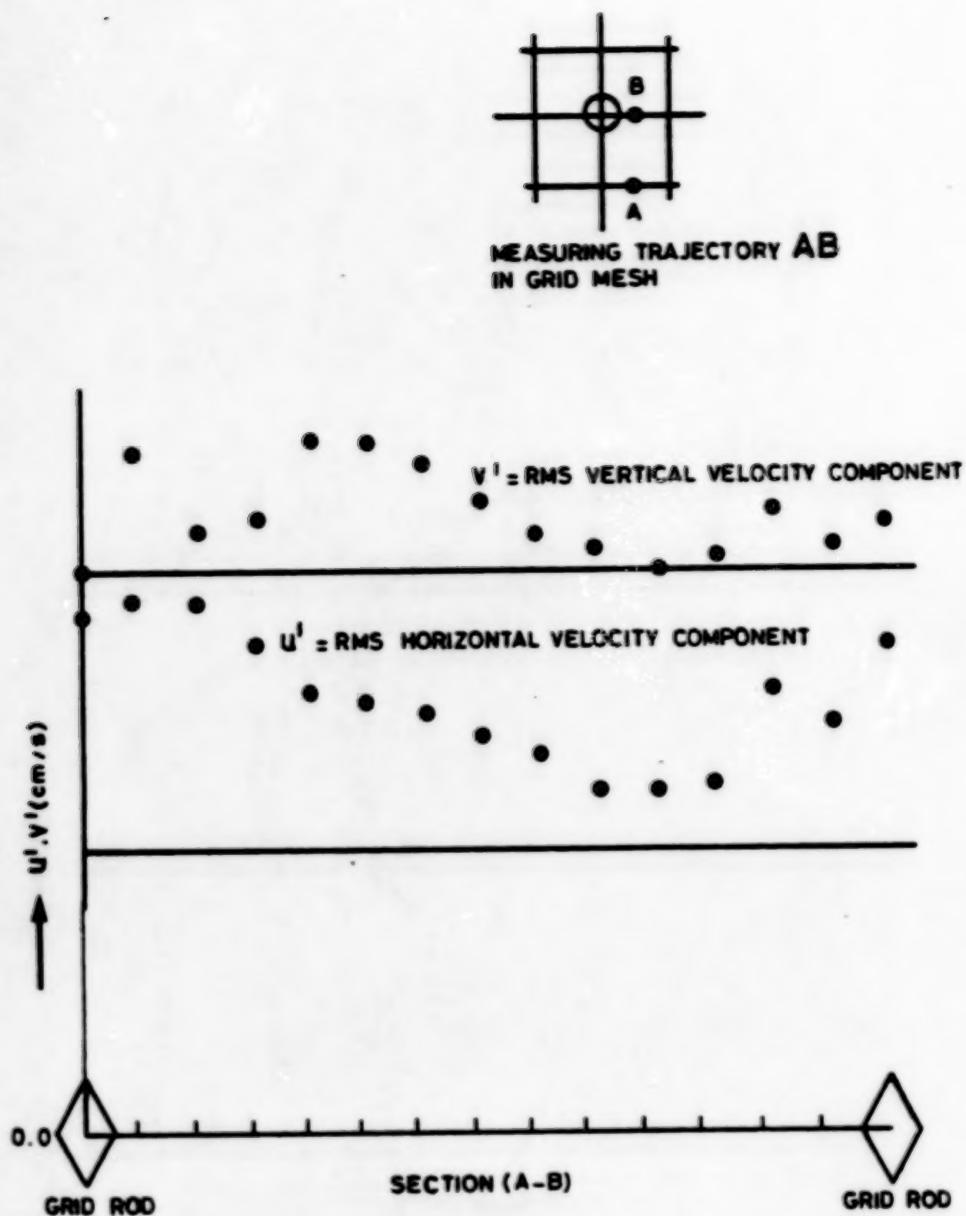


FIGURE A.5 Turbulent velocity fluctuations along a horizontal section in the column ($f_{\text{grid}} = 0.2 \text{ s}^{-1}$)



FIGURE A.6 Heat-insulated grid column for low-temperature experiments

$$e = 55 f_{\text{grid}}^3 \quad (\text{J/s m}^3)$$

with $f_{\text{grid}} = \omega/2\pi$

The homogeneity of the turbulence was checked with a laser-doppler velocity meter. The turbulent velocity fluctuations in the horizontal and vertical direction are of the same order of magnitude, and are almost homogeneous in the horizontal area. An example of these measurements is shown in Figure A.5.

The water temperature in the column is an important parameter because it influences the oil viscosity. Moreover, temperature differences in the column can generate density currents that disturb the observation of the rise velocity W of oil droplets. Therefore, the whole column is placed in a water filled tube connected with a thermostat bath to keep the column at a specific and homogeneous temperature. The temperature of the column water was varied from 4°C to 20°C during the different experiments. To attain low temperatures, the entire column was covered with an insulation blanket, see Figure A.6a.

A.1.2 Oil Flume

The experiments performed in the Oil Flume concern the effect of breaking waves (at laboratory scale) on a surface oil layer characterized by the following parameters:

- ratio of dispersed oil and surface oil
- droplet size distribution of dispersed oil
- vertical distribution of dispersed oil.

The Oil Flume was constructed in 1983 to allow fundamental laboratory research into the natural and chemical oil dispersion processes.

A schema of the flume with basic equipment is shown in Figure A.7. The body of the flume is 15 m long, 0.5 m wide and has a maximum water depth of 0.6 m. All parts of the flume that may come into contact with the oil

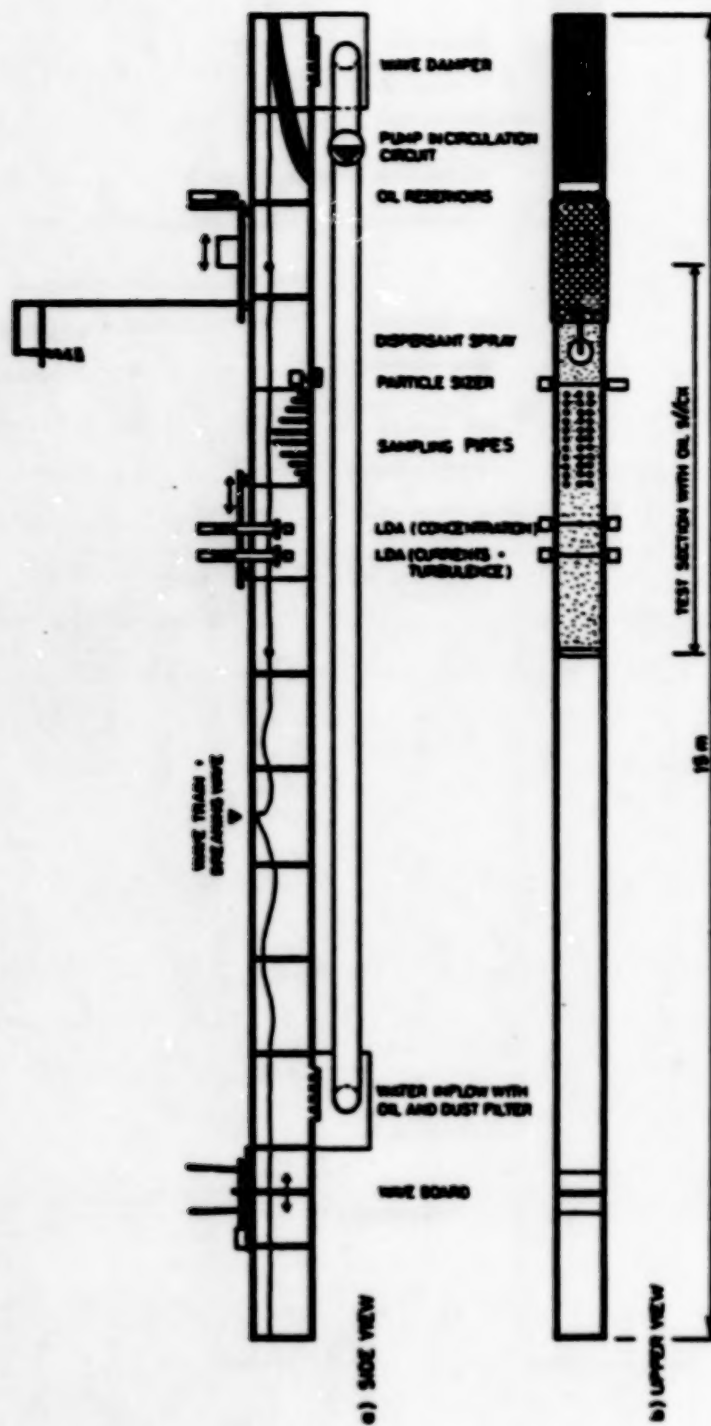


FIGURE A.7 Schematic Oil Flume with basic equipment



FIGURE A.8 Oil flume with wave board

are made of glass or resistoplast-coated steel, stuck together with silicon glue. These materials are not affected by oil, chemical dispersants, and cleansing detergents and will not influence the surface tension of the water and the oil, nor the oil-water interfacial tension.

The walls and bottom of the flume consist mainly of glass to allow visual observation as well as the direct (in-situ) detection of dispersion parameters by laser beams.

Breaking waves are essential for the study of oil dispersion. The wave-board in the flume can generate a distinct pattern of irregular waves. The generation of a single breaking wave in the flume can take place by radiating a wave train from the programmed wave board, where the wave train is characterized by a specific wave height distribution and wave period distribution. The wave train components determine the location, duration, height and intensity of the breaking wave. The maximum wave height is about 0.25 m at a water depth of 0.5 m. A wave damper has been mounted at the end of the flume. A photograph of the flume with the wave-board section is shown in Figure A.8.

The flume is supplied with a flow circuit and a set of pumps to generate a flow velocity of up to 0.5 m/s at a water depth of 0.5 m. Brine can be added to the flume to attain the proper water salinity. The flume is situated in a workshop where the air temperature is kept at a constant level of 18°C. Normally the temperature of the water (withdrawn from cisterns under the workshop floor) will be 16 to 17°C. In special cases the temperature of the water can be changed by adding warm water or ice to the flume.

Cleansing the flume of oil (and chemical dispersants) is performed by a hot water gun, initially with addition of soap and finally by hot water only. The control of the cleaning is carried out by measuring the surface tension of the water in the flume. (The same procedure was applied for cleaning the grid column).

Withdrawal pipes with different lengths were mounted in the test section of the flume to withdraw water samples from different depths (see Figure A.7).

Measuring equipment

The following parameters are important to the dispersion process:

- a) wave pattern and orbital movement
- b) current velocity
- c) turbulence structure in the water mass
- d) oil layer thickness h_o
- e) oil concentration in water
- f) droplet size distribution of dispersed oil

These parameters can be measured by the following methods:

Item a: The wave profile is obtained by a small (1 cm) pressure indicator just below the water surface. A constant vertical distance to the water surface is maintained by an electromotor coupled with the output of the pressure indicator.

A laser-doppler velocity meter can be applied to measure the orbital movement. The apparatus is mounted with an adjustable frame (vertical position) on a movable cart (horizontal position).

Item b: The current velocity and/or velocity profiles can be measured by a micropropellor meter.

Item c: The measurement of the turbulence structure in a flow is performed by the laser-doppler velocity meter as described in sub-section a. However, the turbulent structure in the bore of a breaking wave cannot be derived with this equipment because the interruption of the beam by air bubbles in the bore prevents the receiver from registering the signal.

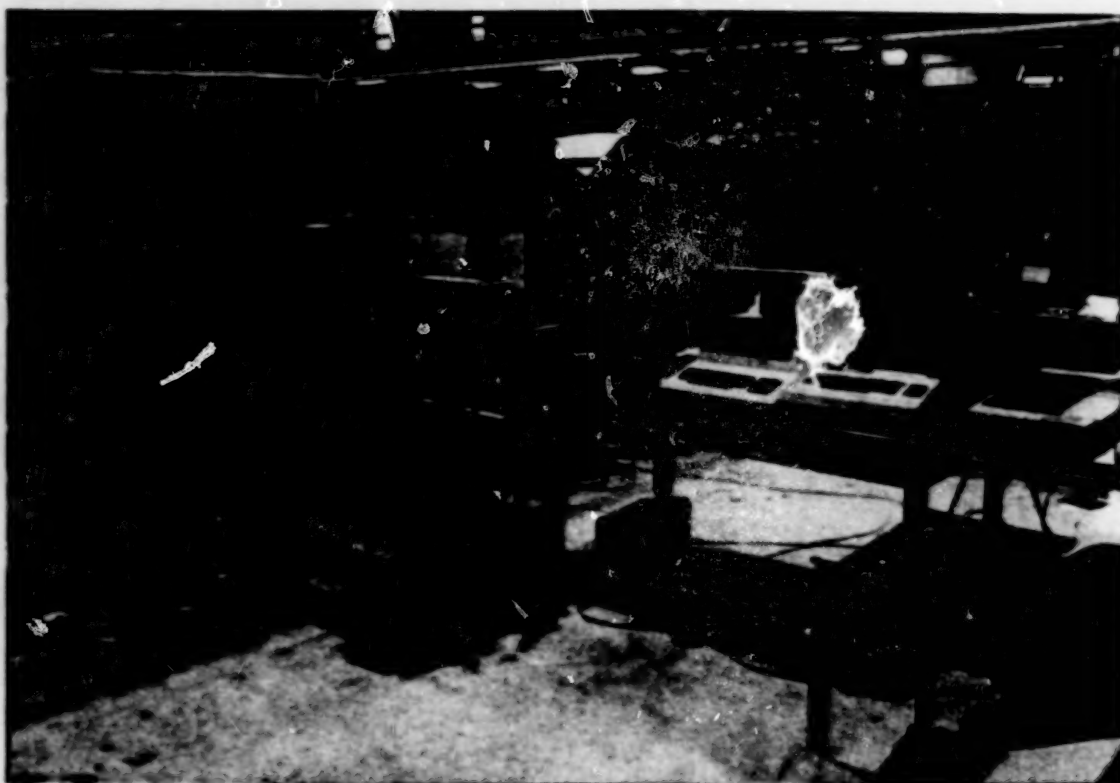


FIGURE A.9 Oil flume with two laser-beam particle sizrs

Item d: The oil layer thickness h_o and the homogeneity of h_o can be derived with a gauge needle. The contact of the vertically movable needle with the oil surface can be observed visually, while the oil-water interface is indicated by an electric signal making use of the conductable (water) and non-conductable (oil) characteristics of the two layers.

Item e: The concentration of dispersed oil in the flume can be measured by the following three methods:

- e1) infra-red spectroscopy on oil water samples withdrawn by the tubes in the measuring section. The spectroscopic method is described in Section A.3.1.
- e2) laser beam adsorption. A quick but rough method of in-situ concentration measurement is the adsorption of a laser beam on its way through the flume. Assumptions (or measurement, see item f) should be made about the droplet size distribution of the dispersed oil.
- e3) particle sizes. The concentration of dispersed oil can be determined by the integration of the measured droplet size distribution curve (see item f).

Item f: Two methods were applied for the determination of oil droplet size distribution in the flume:

- f1) A Malvern laser-beam particle sizer was applied for in-situ measurements. The apparatus and the limitations of measurements are described in Section A.2.1.

The apparatus was mounted across the flume with the emitter and receiver on opposite sides of the flume and the laser beam crossing the 0.5 m wide water mass with dispersed oil. Figure A.9 shows the flume with two laser-beam particle sizers for measurements on different depths below the water surface.

- f2) Visual microscopy with oil-water samples taken at different locations. The method is described in the sections A.2.2. and A.2.3.

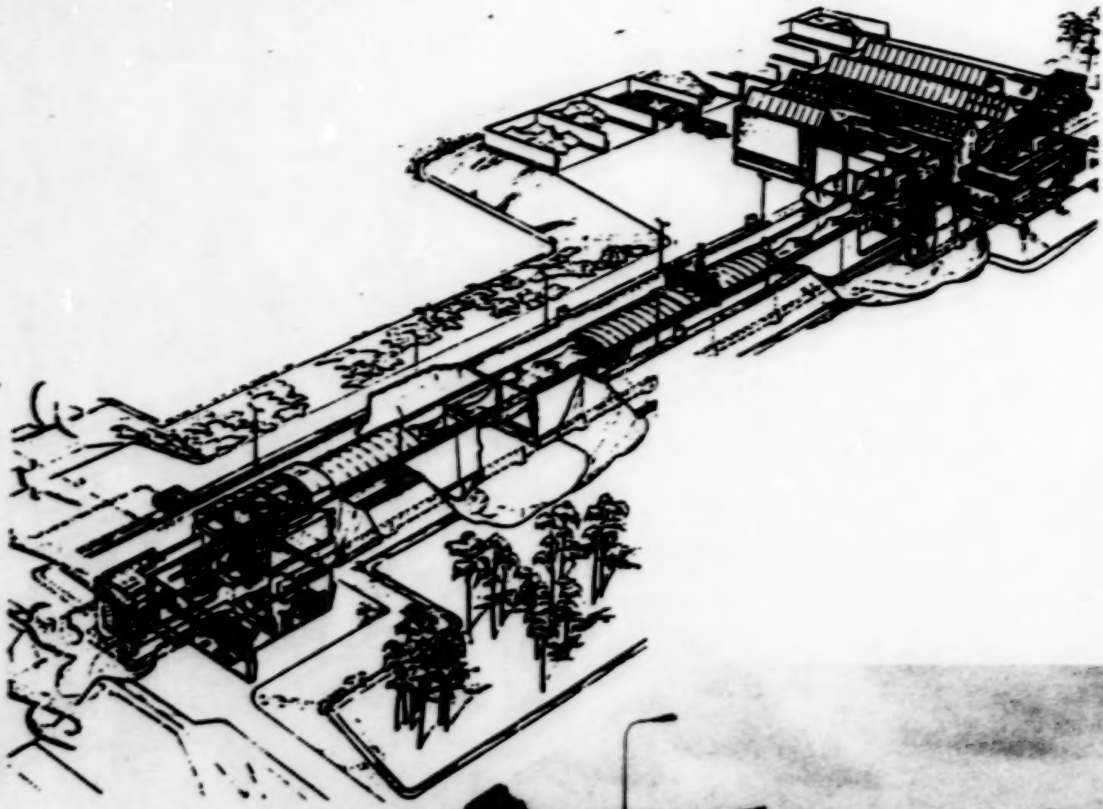


FIGURE A.10 Delta flume

A.1.3 Delta Flume

The Delta Flume was constructed for large-scale physical modelling. The open-air flume is shown in Figure A.10. The length of the flume is 240 m, the width 5 m and the depth 7 m, with deeper sections down to 9.5 m.

Monochromatic and random waves with a height of up to 2 m can be generated according to a required time history. The wave period can vary from 1 to 12 s. The flume is filled with fresh water, salt water cannot be supplied.

A wide range of instruments is available to monitor the hydraulic processes. In the present study, wave height meters were used before and beyond the breaking wave location, in order to calculate the energy dissipation in the breaking wave.

The length, width and height dimensions of the Delta Flume are ten times larger than the dimensions of the Oil Flume. The breaking waves in the Delta Flume, with wave heights up to 2 m, are of the same order of magnitude as waves in field conditions. Five oil dispersion experiments in the Oil Flume were scaled up and carried out in the Delta Flume to determine the relation between the small-scale laboratory conditions in the Oil Flume to "field" conditions in the Delta Flume.

Much effort was spent on the design of programs for the wave generators in the Oil Flume and Delta Flume, in order to generate suitable breaking waves with different breaking energy levels and vertical penetration by the orbital movement and turbulence field. The breaking waves must be accurately reproduced in the areas of observation and must be transformable from the small Oil Flume to the large Delta Flume.

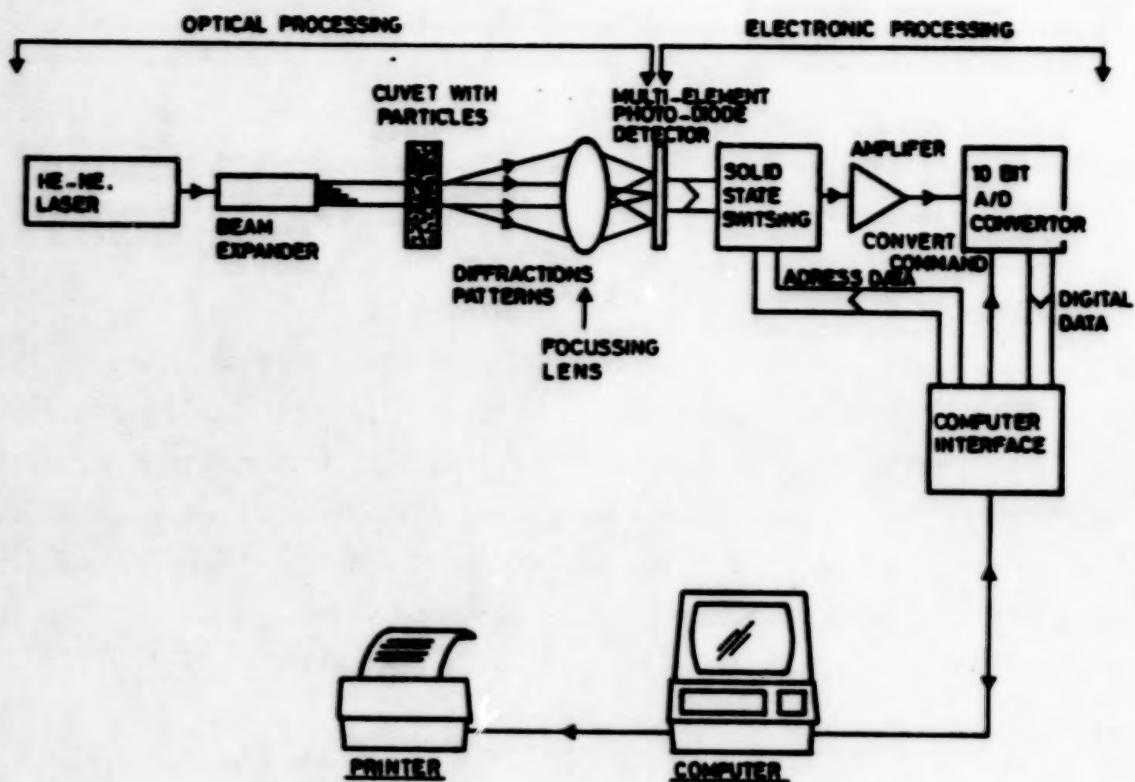


FIGURE A. 11 Schematic laser-beam particle sizer

A.2 Laboratory Equipment and Measurement Techniques

A.2.1 Laser Beam Particle Sizer LBPS

The apparatus

A Malvern 2600 D Laser Beam Particle Sizer (LBPS) was used in many experiments for determination of the oil droplet and SPM particle size distribution. The scheme of the LBPS is given in Figure A.11.

The Malvern Particle Sizer uses the principle of Fraunhofer diffraction. A laser transmitter produces a parallel, monochromatic beam of light to illuminate the particles in a sample. The incident light is diffracted by the particles to give a stationary diffraction pattern regardless of particle movement. A Fourier transform lens focusses the diffraction pattern onto a multi-element photo-diode detector consisting of thirty concentric elements. The detector is interfaced directly to a desk top computer allowing it to read the diffraction pattern and perform the necessary integration digitally. The computer uses the method of non-linear least squares analysis to find the size distribution that gives the closest fitting diffraction pattern. The fitting error (sum of the least squares errors) is given in the measurements by the phrase "best log error = ..." (e.g., Figures III.6 through III.58). The reliability of the measured size distribution is roughly indicated by the following guidelines:

best log error > 6	model not appropriate
5.5 < best log error < 6	poor fit
5.0 < best log error < 5.5	adequate fit
4.0 < best log error < 5	good fit.

The Malvern particle sizer cannot be calibrated, but the transmitter and detector should be carefully aligned. The proper detection of the particle sizes can be tested with gauging fluids containing particles with well-known sizes.

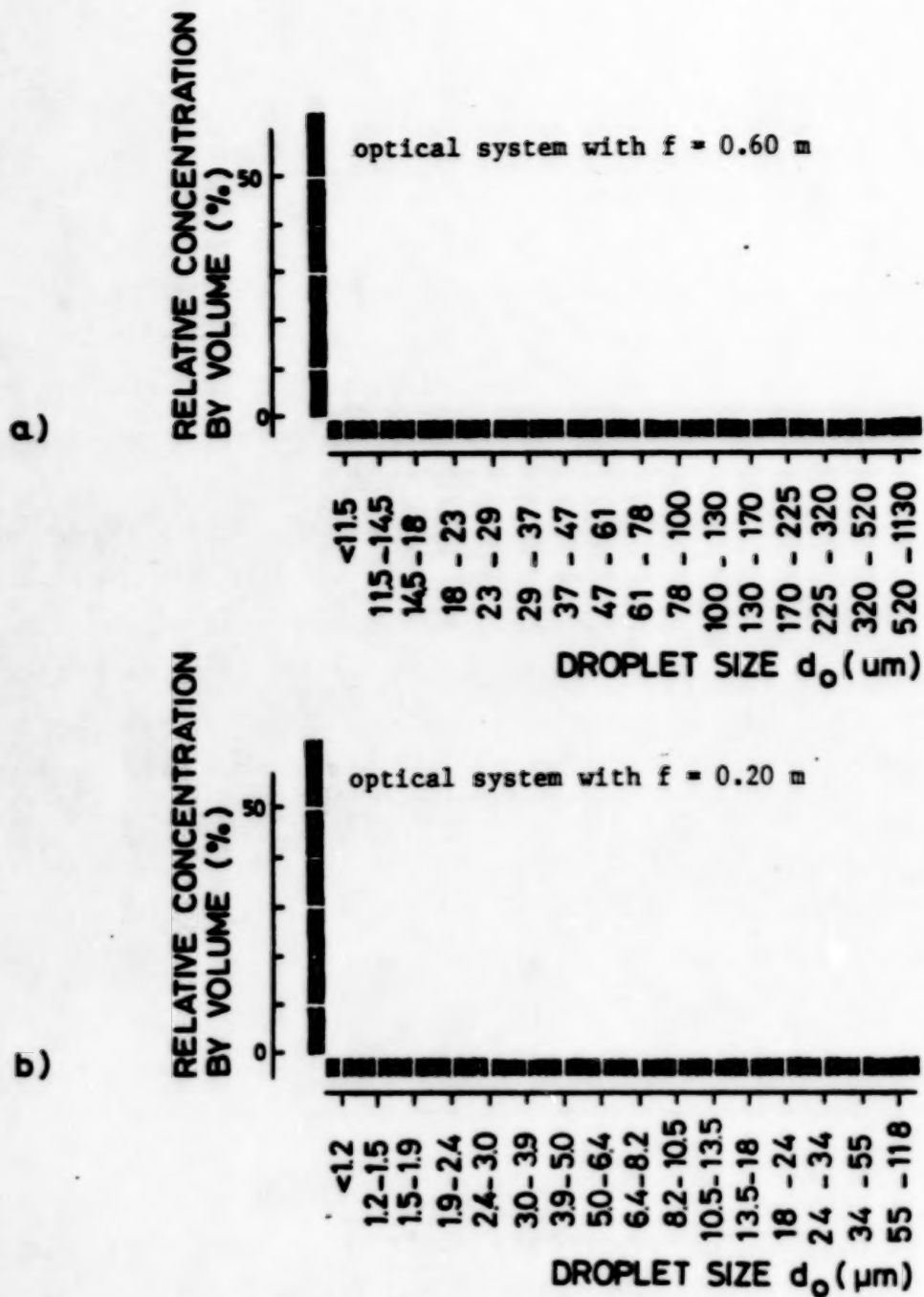


FIGURE A.12 LBPS size ranges of measurement with two different focal distances of the optical system

The LBPS was supplied with the following optical systems for measurement of particle size distributions in different size ranges:

- a) system 1 with focussing length of 0.6 m, for measurement of particles in the range from 11.5 to 1130 μm . The particles were divided by the apparatus in sixteen subranges as shown in Figure A.12a.

The long focussing length of this optical system allows a sample cell of 0.6 m or smaller in between the beam expander and the focussing lens (see Figure A.11). This means that the oil flume itself, with a width of 0.5 m, can be used as a sample cell for in-situ measurement of size distributions. A relatively small cuvet was used in the experiments with the grid column, with continuous flow-through of water withdrawn from the column.

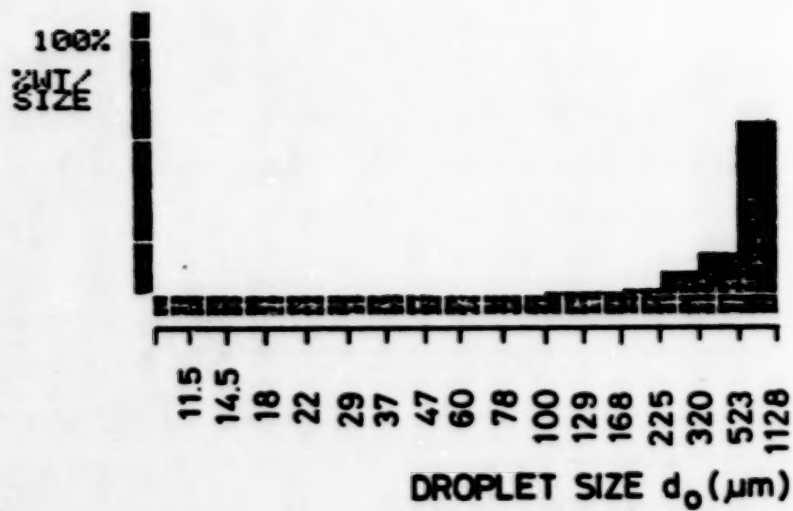
- b) system 2 with focussing length of 0.2 m, for measurements of particles in the range from 1.2 to 120 μm . The sixteen subranges are shown in Figure A.12b. This optical system allows only a small sample cell.

The particle sizer measured the oil concentrations in the various subranges by percent of volume, relative to the volume of oil in the entire size range of measurement (see Figure A.12).

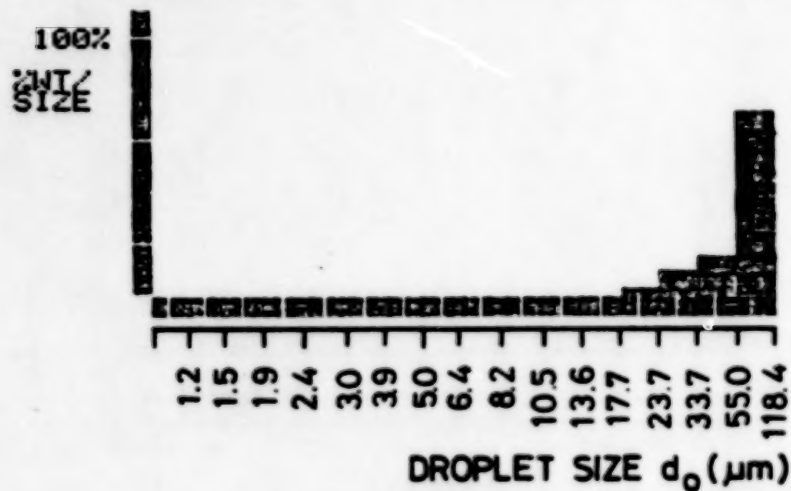
Measurement of droplet size distribution

Many droplet size distributions were measured with the LBPS, equipped with the optical system for measurement of particle sizes in the range from 11.5 to 1130 μm . A typical measured oil droplet size distribution is given in Figure A.13a with droplets down to $d_0 = 100 \mu\text{m}$. (Grid column experiment C55, PB₁₀ oil, $e = 440 \text{ J/s m}^3$, $t_{\text{grid}} = 600 \text{ s}$. See Section III).

The particle sizer measures the oil concentration in a size range by volume. The minimum detectable concentration in a size range is 0.1 percent of the total detectable oil in all ranges. Reliable measurements on oil droplets smaller than 50 μm were never obtained in the grid column experiments while using the LBPS optical system for the 11.5 to 1128



a) range of measurement 11.5 - 1128 μm



b) range of measurement 1.2 - 118 μm

(experiment C55, grid column, PB_{10} , $e = 440 \text{ J/s m}^3$)

FIGURE A.13 Droplet size distributions in experiment C55. LBPS measurements in different size ranges

μm size range. However, replacing this LBPS optical system by another for droplet detection in the 1.2 to 118 μm size range gave different results, as shown in Figure A.13b, with oil droplets down to 20 μm .

Obviously, the smallest detectable droplet size range in a certain size distribution depends on the relative concentration of the small droplets in the subrange with respect to the oil concentration in the entire range of measurement. This is demonstrated in Figure A.14 where imaginary LBPS output is given that should be found for droplet size distributions with $N_u(d_o) \sim d_o^{-2.3}$. $N_u(d_o)$ = number of droplets with sizes in the range from $d_o - \Delta d$ to $d_o + \Delta d$; droplet size distributions with this shape were found in all dispersion experiments. The distributions were calculated with an abrupt end at d_{max} , with different values of d_{max} in Figure A.14.

A single experiment with PE₃ oil, heavily stirred in a beaker with water, showed that very small oil droplets were generated. A sample was removed from the beaker and collected in a small sample cell of the LBPS. The droplet size distribution for this high concentration experiment is shown in Figure A.15, after a stationary position of 18 minutes in the cell to resurface big droplets. The described limitations on the registration of wide particle sizes ranges with widely different concentrations and the apparent occurrence of a wide range of oil droplet sizes in the experiments, have led to the development of an alternative droplet size distribution technique, see Section A.2.2.

A.2.2 Fluorescence and visual microscopy

The fluorescence apparatus

An apparatus was constructed for visual microscopy observation of small oil droplets. Use has been made of the fluorescence behaviour of oil to distinguish oil droplets from SPM or other background particles in the same size range.

A schematic representation of the apparatus is shown in Figure A.16a. The

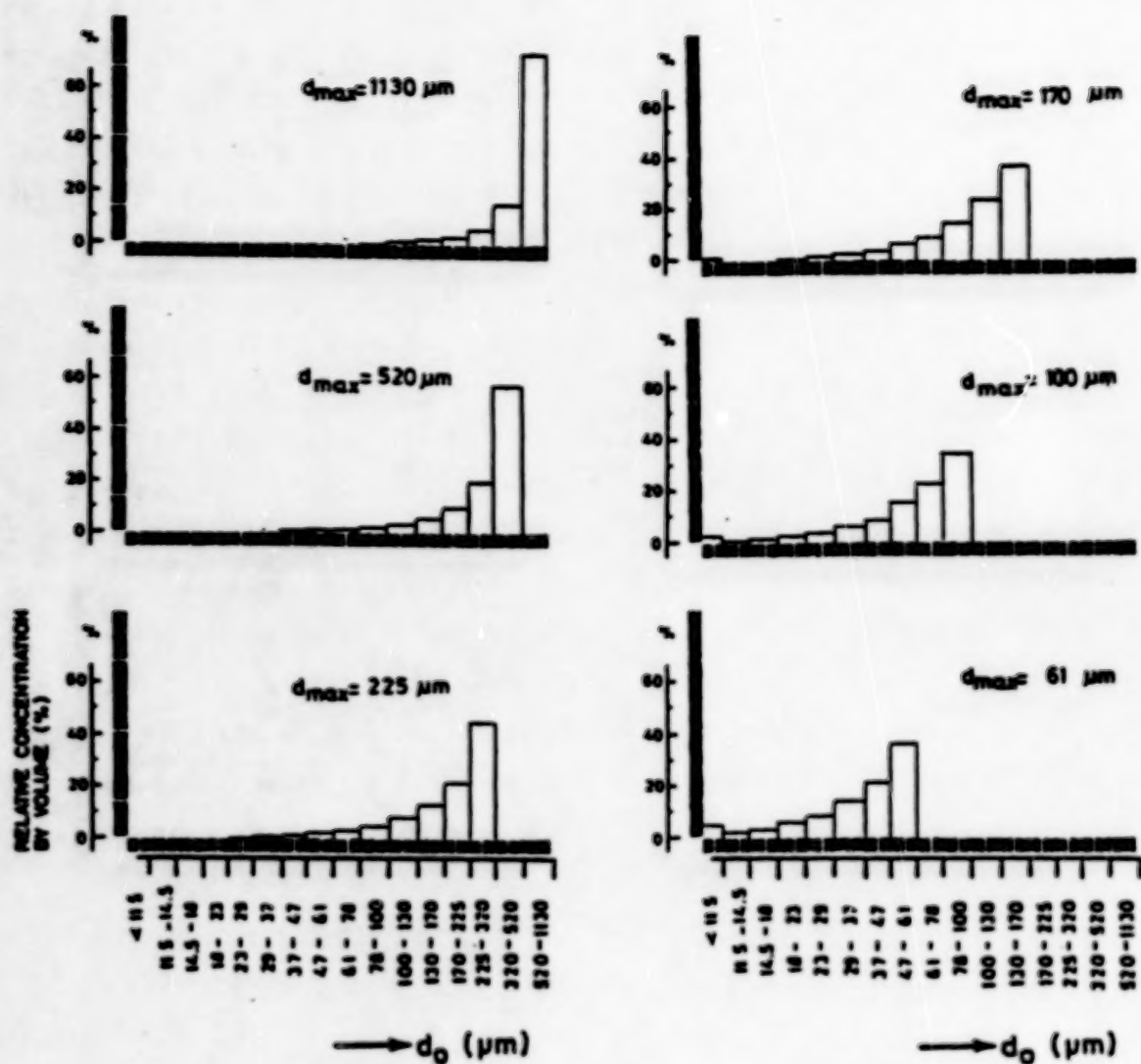


FIGURE A.14 Imaginary LBPS data for $N_U(d_o) \sim d_o^{-2.3}$ distribution, with different values of d_{max}

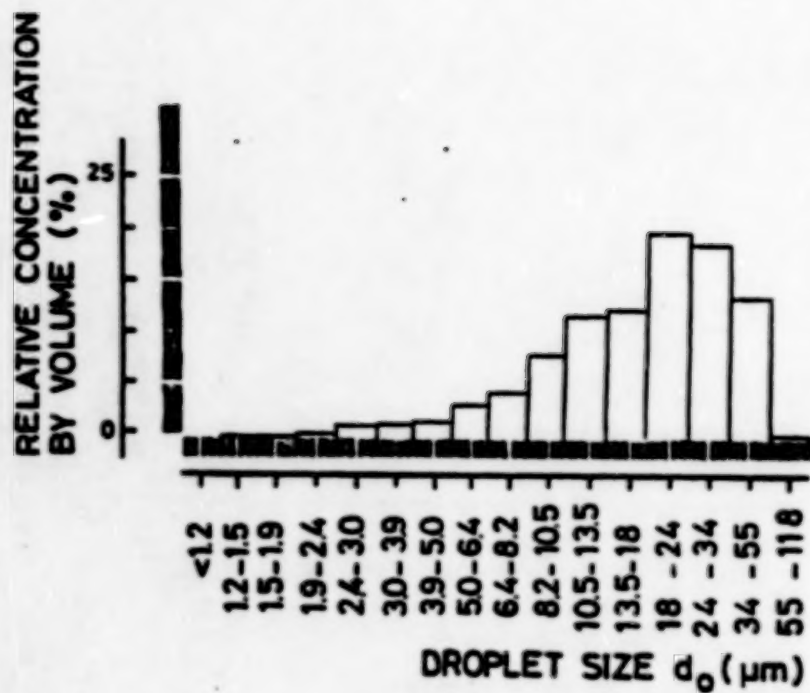
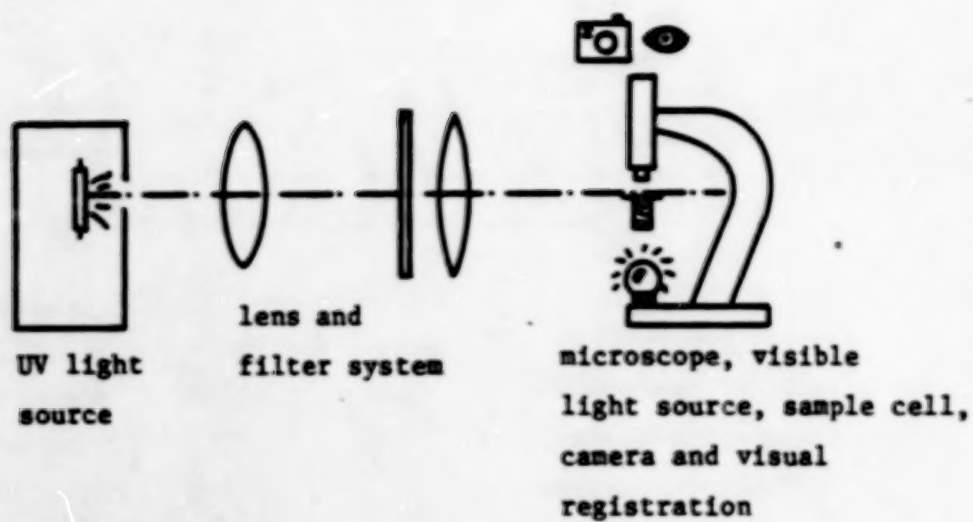
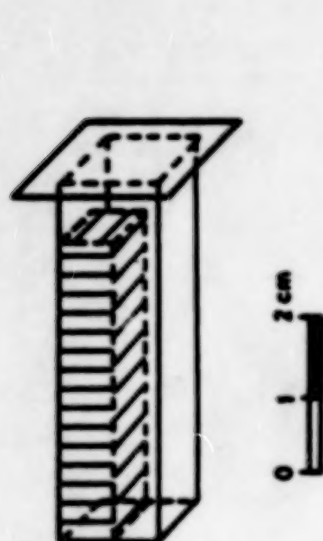


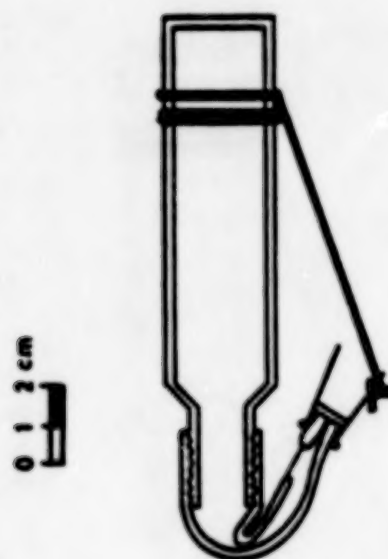
FIGURE A.15 LBPS data in stirred-beaker oil dispersion experiment



a) schematic apparatus

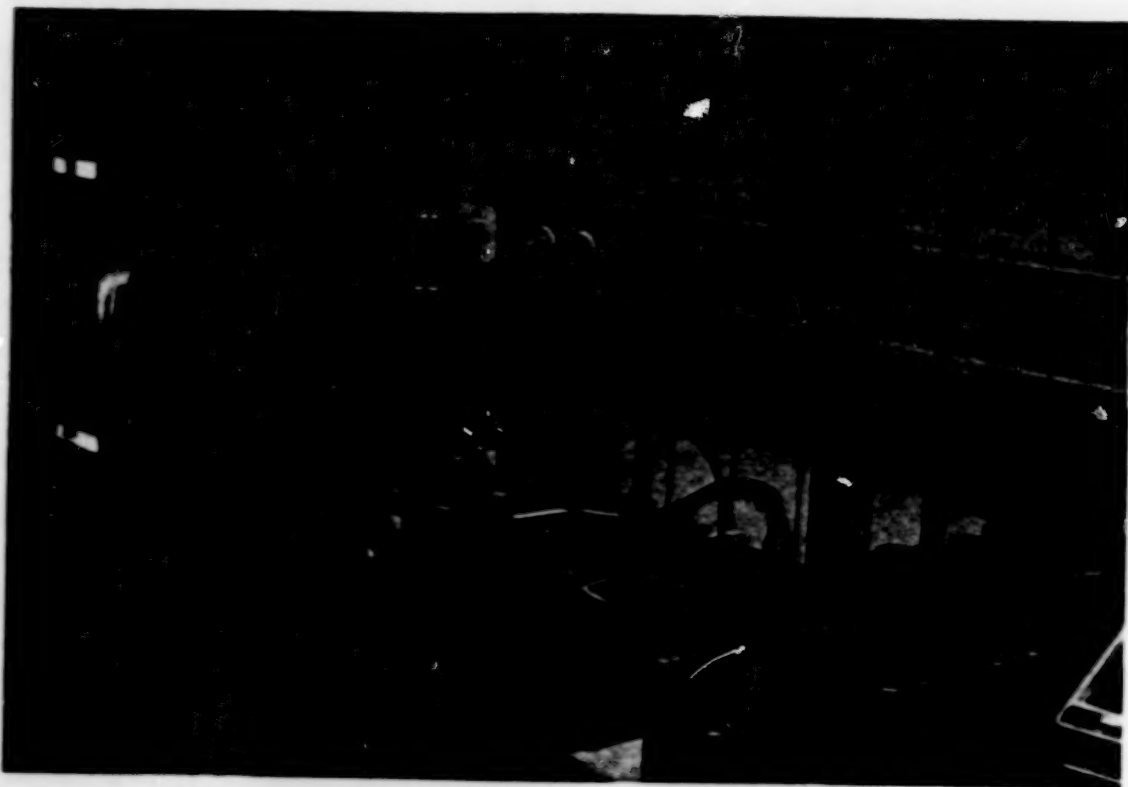


b) sample cell for grid column experiments



c) sampling cell device for flume experiments

FIGURE A.16 Schematic fluorescence apparatus



a)



b)

FIGURE A.17 Fluorescence detection apparatus

sample cell was placed under the microscope. Two light sources were used, an ordinary visible-light source, and an ultraviolet light source. The latter is a mercury high pressure bulb generating a line spectrum where the 365 nm ultraviolet light is highly effective for oil fluorescence in the visible light. A lens and filter system was used in order to concentrate the light on the sample and to restrict the light to a narrow wavelength range around 365 nm. The apparatus allowed the size detection of oil droplets down to about 2 μ m, where the droplets could be distinguished easily from dust or silt particles. Moreover, it was even possible to distinguish oil droplets representative of the two types of oil used in the experiments. The UV light source forced the emission of much more fluorescence light from Ekofisk oil than from Prudhoe Bay crude.

The following types of sample cells were used:

- a) Samples for observation of oil droplets and oiled sediment in the grid column experiments on oil-SPM interaction were usually collected in 10 x 10 x 40 mm plastic sample cells closed at the upper side with 0.15 mm thick loose microscope slides, see Figure A.16b. Buoyant oil droplets with sizes $d_o > 5 \mu$ m will rise to the surface slide within a few hours, and can easily be observed and photographed with the microscope. The enlargement usually applied is 40x or 100x, and occasionally 180x or 450x. In almost all cases the cell was partly filled up with a 10 x 5 x 36 mm perspex bar to divide the cell into a part with a depth of 4 mm, and a part with a depth of 40 mm. For the observation of buoyant oil droplets, taking into consideration a certain time of stationary position, fewer oil droplets were surfaced above the shallow part of the cell, but the smallest droplets are represented more completely.

The distance between the microscope objective lens and the subject must be about 8 mm for 100 x enlargement, and much smaller for greater enlargements. Therefore suspended sediment in the sample cell can be observed only through the surface slide on top of the perspex bar.

- b) Another type of sample cell is shown in Figure A.16c. In-situ withdrawal of oil-water samples in oil flume and delta flume experiments

was carried out with this type of sampler. (See also Section A.2.3). After sampling, the sampler was kept in stationary position for about twenty hours to allow oil droplets with $d_o \geq 5 \mu m$ to rise to the surface. The tube has a flat top glass, thickness 1.5 mm, and is placed directly under the microscope. The enlargement was usually 72x during the measurement of the oil droplets.

The photograph in Figure A.17a shows the UV source, microscope and a set of samplers. The fluorescent UV beam is visible on the flat top glass of the samples due to a (weak) fluorescence of the glass. (Figure A.17b)

A discussion on the probability of particle or droplet collisions due to differential settling or Brownian motions in the stagnant sample cells is given in Section A.4.

The microscope was applied with a camera. Examples of micrographs from buoyant (surfaced) oil droplets, buoyant droplets coated with SPM particles, and sedimented SPM flocs with encapsulated oil droplets are shown in Section IV. The following remarks are made with respect to the possibilities and quality of the micrographs, which were restricted considerably by the limited depth of field of the camera, and the limited contrast resolution of photographic film and paper:

- a) Buoyant uncoated oil droplets were most easily observed and photographed. The depth of field of the camera was about 15 μm at 100x. The droplets were located on a plane level against the surface glass. Photographs were very useful for measurements of droplet size distribution. (See the micrographs in Figure IV.7).
- b) Observation of the SPM coating of small buoyant oil droplets required a microscope enlargement of 180x or 450x. (See the micrographs in Figures IV.8 and IV.17). Even visual observation of a single SPM-coated oil droplet required scanning over the droplet depth by changing the focusing depth, in spite of the relative large depth of field allowed by the eye's accommodation characteristics. The depth of field of the camera was much less, and resulted in the relatively poor micrographs shown in Section IV.

c) Most problems with the limited depth of field and contrast resolution characteristics of the camera and film occurred with observation of SPM flocs with encapsulated oil droplets. The oil-SPM agglomerates were three-dimensional with depths up to the order of magnitude of 100 μm . The difference in depth of field between the eye and the camera is very remarkable in case of oil-SPM agglomerate observation.

Moreover, the contrast range that can be covered by the eye is much more extensive than for film and photographic paper. The following requirements for light contrast must be fulfilled for useful observation of SPM flocs with encapsulated oil droplets:

- c1) on the one hand, the high contrast between the fluorescence light of small droplets ($d_o = 5 \mu\text{m}$) and big droplets ($d_o = 50 \mu\text{m}$) must be detected.
- c2) on the other hand, the low contrast between the fluorescent oil droplets and the light reflected from the silt particles must be resolved.

The restricted capabilities of the camera and the film resulted in the relatively poor photographs in the figures in comparison to the clear and beautiful visual observations.

The preceding description indicates that the fluorescence apparatus including the microscope and camera had the following possibilities:

- a) clear distinction between oil droplets and silt particles by fluorescence of the former.
- b) clear distinction between Ekofisk oil droplets and PB oil droplets because of a difference in fluorescence behaviour. Ekofisk droplets were considerably brighter than PB droplets. PB₀, PB₃ and PB₁₀ could not be distinguished in this way.
- c) quantitative determination of droplet size distributions in oil break-up experiments by droplet counting either from photographs or by direct visual observation.
- d) qualitative visual observation of the coating of oil droplets with silt particles.
- e) partly quantitative and partly qualitative determination of oiled sediment by visual observation. The type of oiling could be obser-

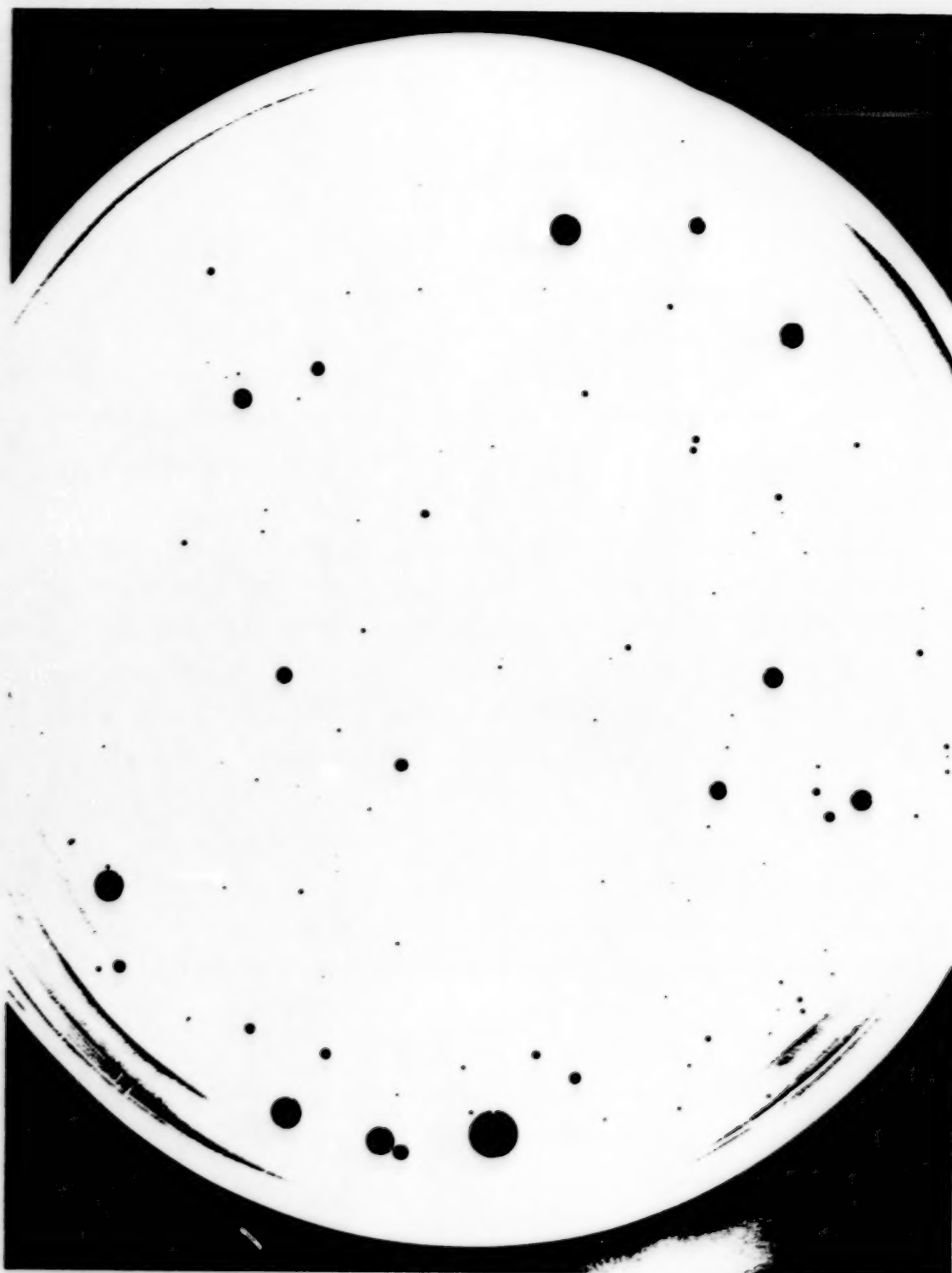
ved (e.g., distinction between the encapsulation of oil droplets, and coating of SPM particles with oil). The maximum and minimum droplet size in the flocs could be observed, including a rough indication of the droplet size distribution.

Determination of droplet size distribution

Two methods were applied for determination of droplet size distribution of dispersed oil. The determination by the laser-beam particle sizer is described in Section A.2.1., and was applied in the grid column experiments and in the first series of Oil Flume experiments. The second method consisted of visual scanning and counting of oil droplets in a sample, making use of the fluorescence apparatus, the microscope and a 35 mm camera.

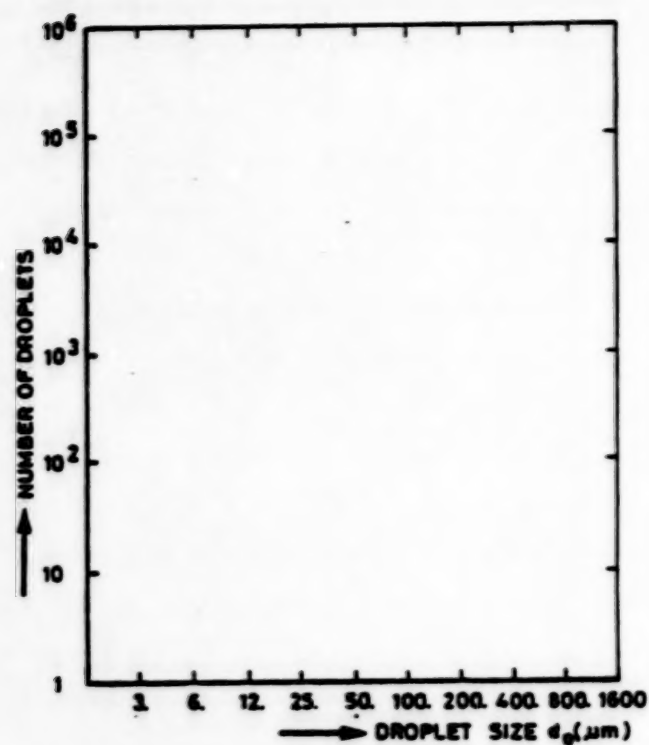
Determination of droplet size distributions by visual scanning was applied in the second series of Oil Flume experiments and in the Delta Flume experiments. The oil-water samples were withdrawn from the laboratory flumes by the samplers described in Section A.2.3. (See also Figure A.16c). After sampling, the samplers were kept in vertical position during a certain time to allow the buoyant oil droplets to rise to the flat top glass.

The surface oil droplets in the sampler with droplet sizes $d_o > 50 \mu\text{m}$ could be measured from photographs taken from the top glass. The diameter of the sampler top glass was 27 cm, and the pictures were taken on a 1 : 1 scale on the negative. The pictures were taken against the light with an ordinary (visual) light source. Many such photographs are presented in the Sections V and VI. One of these photographs is shown in Figure A.18. Scanning and counting of droplets took place from the negatives projected on a screen. The droplets were divided in size classes shown in Figure A.19a. The number of droplets in a sample with $d_o \geq 50 \mu\text{m}$ was generally low enough to scan the entire top glass of the sampler. (Typical numbers are 3 droplets in the 800 to 1600 μm size range to 100 droplets in the 50 to 100 μm range).

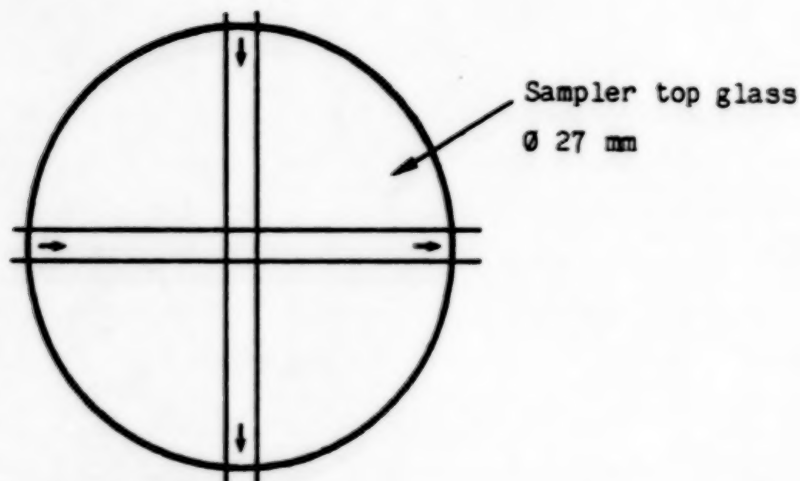


0 1 cm

FIGURE A.18 Photograph of oil droplets in sampler



a) oil droplet size classes for visual counting of droplets



b) minimum scanning trajectories with visual microscopy

FIGURE A.19 Visual determination of oil droplet size distribution

Droplets in the size range $d_o < 100 \mu\text{m}$ were measured and counted by visual microscopy. The sampler was placed directly under the microscope. (The quality of the top glass was good enough to do so). The design of the samples enabled routine oil droplet measurement down to $d_o = 3 \mu\text{m}$. The restriction to $3 \mu\text{m}$ was due to the enlargement of the microscope in relation to the thickness of the top glass, and the reasonable resurfacing time of the droplets. (Generally, a surfacing time of 20 hours was applied). An UV light source was applied during visual microscopy. The fluorescence of the oil enabled a clear distinction between oil droplets on the one hand, and dust, air bubbles and salt crystals (from the brine) on the other hand.

Determination of the droplet size distribution by microscopy took place with a microscope enlargement of 72x. The diameter of the field of vision was 2 mm. The droplets were divided in size classes shown in Figure A.19a. The number of droplets in the size classes with $d_o \leq 100 \mu\text{m}$ was frequently high enough to restrict the scanning area to two perpendicular trajectories (2 mm wide) as shown in Figure A.19b.

A.2.3 Sampling Device

Measured oil droplet size distributions with the LBPS and observations with the microscope indicated that the LBPS was not enable of measuring the size distribution over a wide range of droplet sizes. In principle, oil droplets with sizes down to about $2 \mu\text{m}$ can be detected with the microscope, and the determination of the droplet size distribution is possible by scanning and counting a sample with visual microscopy. Therefore, it was decided to develop a sampling method to obtain proper oil - water samples from the laboratory measurement facilities that can be scanned with the microscope.

The developed sampling device consists of a commercially available cylinder glass with an optically perfect plane bottom. (The cylinder glass was used in the sampler in upside-down position). Figure A.20 shows the sampling device on almost full-scale. The cylinder is provided with a glass nozzle and a flexible silicon tube, closed at the other end with a

paper clamp. A hole is made in the tube near the paper clamp. The sampler can be closed by bending the tube close to the connection with the cylinder. The tube is bent by pulling the rope connected with the paper clamp.

For the purpose of sampling water with oil droplets, the device is filled in advance with heavy brine (or any other suitable heavy fluid). The sampler is brought into the laboratory vessel with the tube in bent position. (See Figure A.21a). At the time of sampling, the rope is loosened, the silicon tube stretches and water penetrates the cylinder by flow exchange (Figure A.21b). The flow exchange rate and the turbulence generated in the tube can be regulated by adjusting the density difference between the fluids inside and outside the sampler and by adjusting the hole size. After sampling, the device is closed again by pulling the rope. (Figure A.21c).

Twenty samplers were used for the measurements reported in the Sections V and VI. The total volume of the sampler is about 60 cm^3 . The samplers were filled with brine with a density $\rho = 1159 \text{ kg/m}^3$, while the water density in the Oil Flume was $\rho_w = 1025 \text{ kg/m}^3$ ("seawater") and $\rho_w = 1000 \text{ kg/m}^3$ in the Delta Flume (fresh water). The volume of the exchanged liquids during sampling was derived afterwards by measuring the water density in the sampler.

The following exchange volumes were determined:

sampling time of 10 s leads to volume exchange of 8 cm^3
sampling time of 30 s leads to volume exchange of 20 cm^3
sampling time of 60 s leads to volume exchange of 35 cm^3
sampling time of 120 s leads to volume exchange of 45 cm^3 .

After sampling, the samplers were taken out of the laboratory vessel and were kept in vertical position during a certain time. The oil droplets rose to the top glasses. The droplets in the size range $d_o > 50 \mu\text{m}$ were measured and counted by taking photographs of the top glasses. Droplets in the size range $d_o < 100 \mu\text{m}$ were measured and counted by visual microscopy, see Section A.2.2.

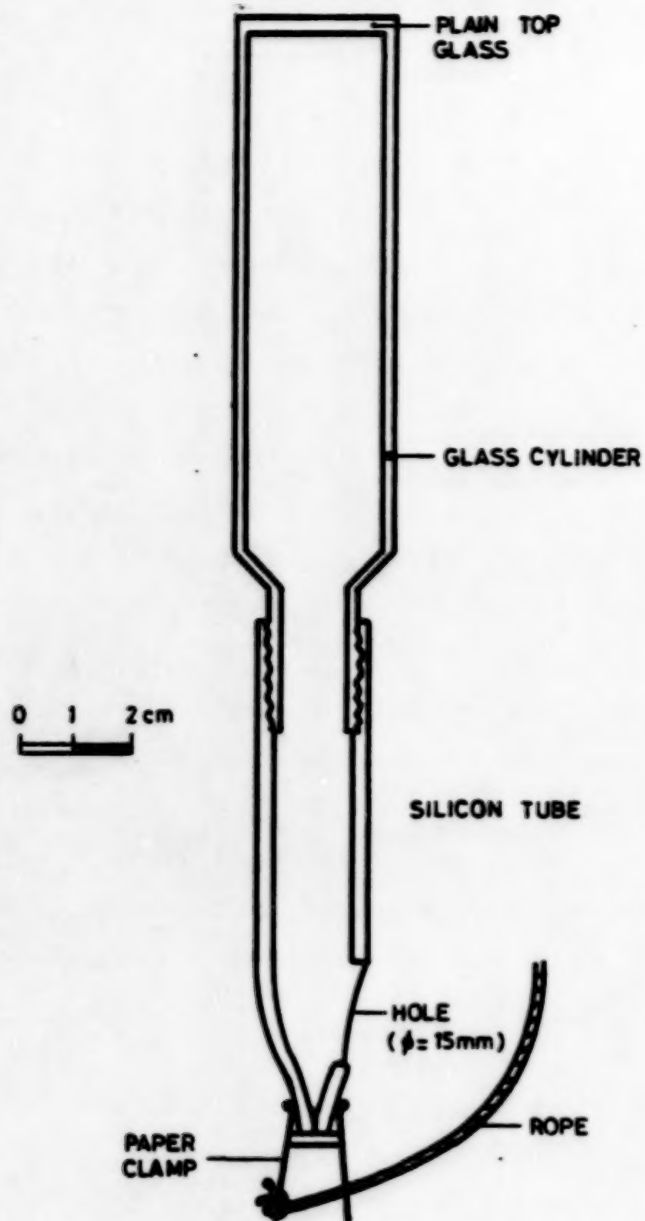


FIGURE A.20 Sampling device for oil-water samples

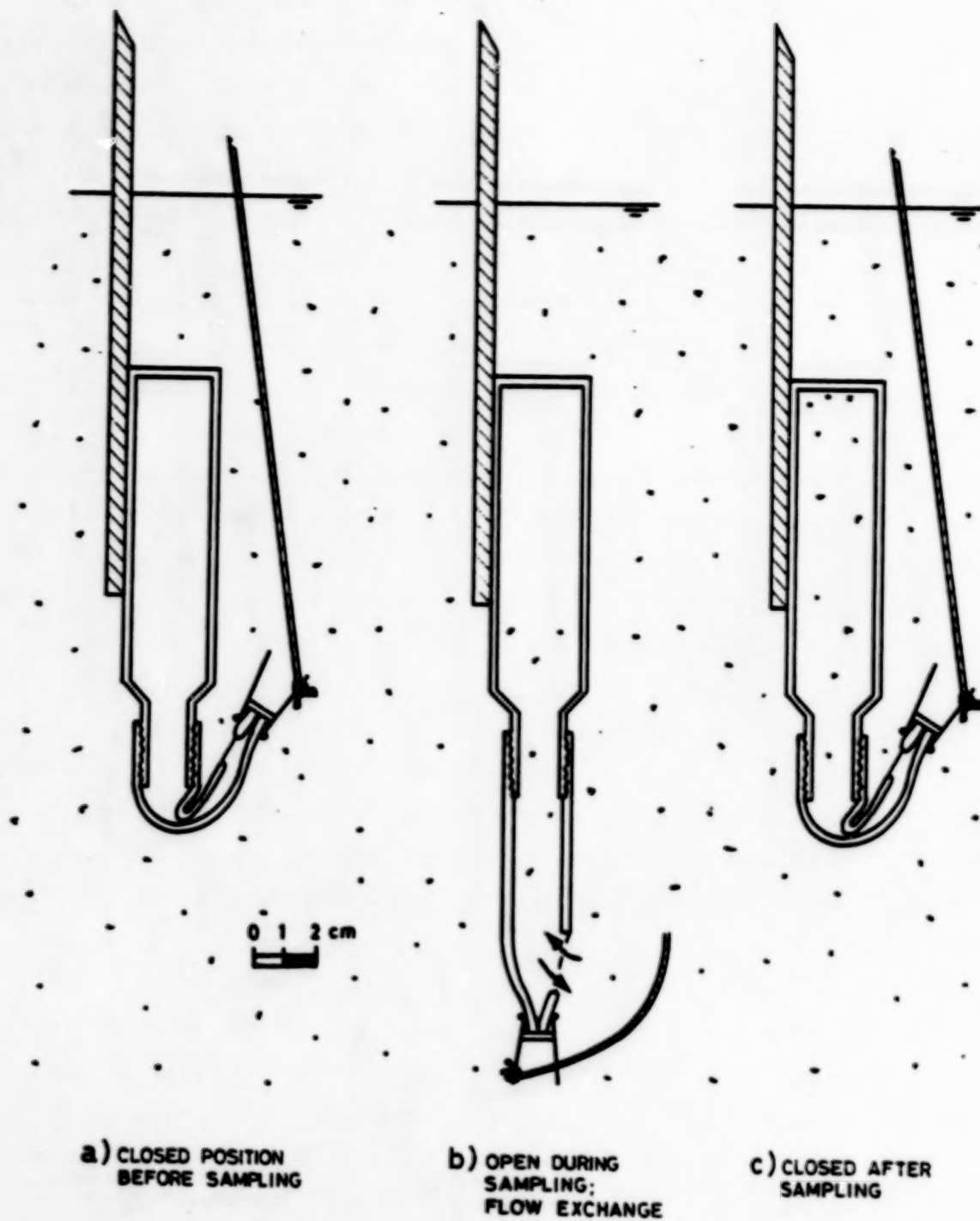


FIGURE A. 21 Sampler in different positions

A.2.4. Sampling methodology for chemical analysis

Chemical analysis was performed on the different types of oil applied in the experiments: Ekofisk oil (unweathered), Prudhoe Bay oil (PB₀) unweathered, and Prudhoe Bay oil weathered by evaporation in laboratory conditions during 3, 10 and 36 days (PB₃, PB₁₀ and PB₃₆ respectively). Analyses of hydrocarbon compounds were performed on whole oil samples by gas chromatography with flame ionization detection (FID-GC). The gas-chromatograms are given in the Figures A.22 to A.26.

The flume experiments on the break-up of surface oil films by breaking waves and the grid column experiments on the break-up of submerged oil parcels in a turbulent ambience were conducted after application of one of the mentioned oil types. The experiments themselves succeeded over a short time (up to ten minutes in the grid column, while in the flume experiments the detection of the droplet size distribution, or sampling for detection, took place shortly after the passage of a single breaking wave). Consequently, it made no sense to conduct chemical analyses on dispersed oil droplets in the oil break-up experiments.

A different situation occurred with the oil-SPM interaction experiments in the grid column. The duration of the experiments was up to three hours (and in a few cases even 50 hours). It is expected that the composition of the oil is an important parameter in the interaction process, and fractionation of the small interacting droplets could occur by dissolution and evaporation of certain compounds during the experiments.

Chemical analyses were conducted on "water" samples removed from the grid column during the oil-SPM interaction experiments, in order to determine the amount of oil and the hydrocarbon composition of the oil in the different phases (see below). Table IV.3 surveys the 135 samples from the grid column experiments and the results of the GC analyses.

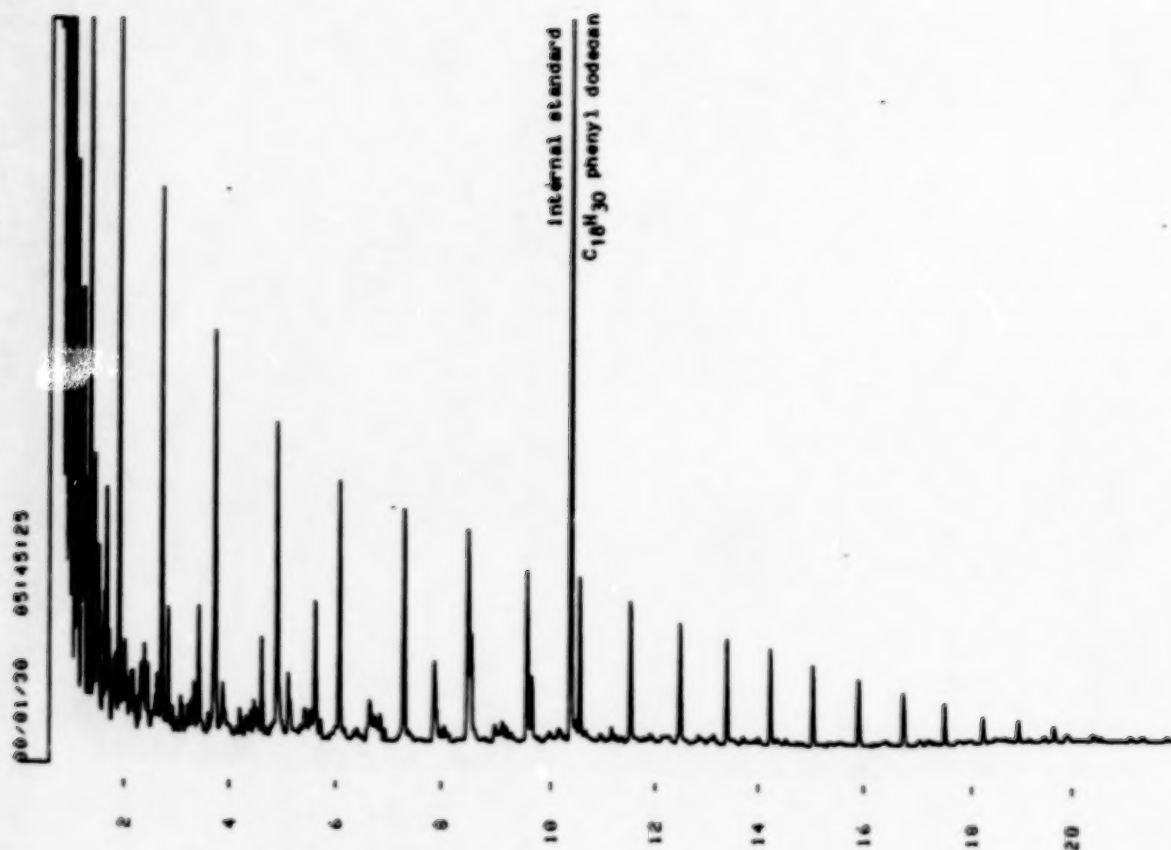


FIGURE A.22 Gas chromatogram of Ekofisk oil

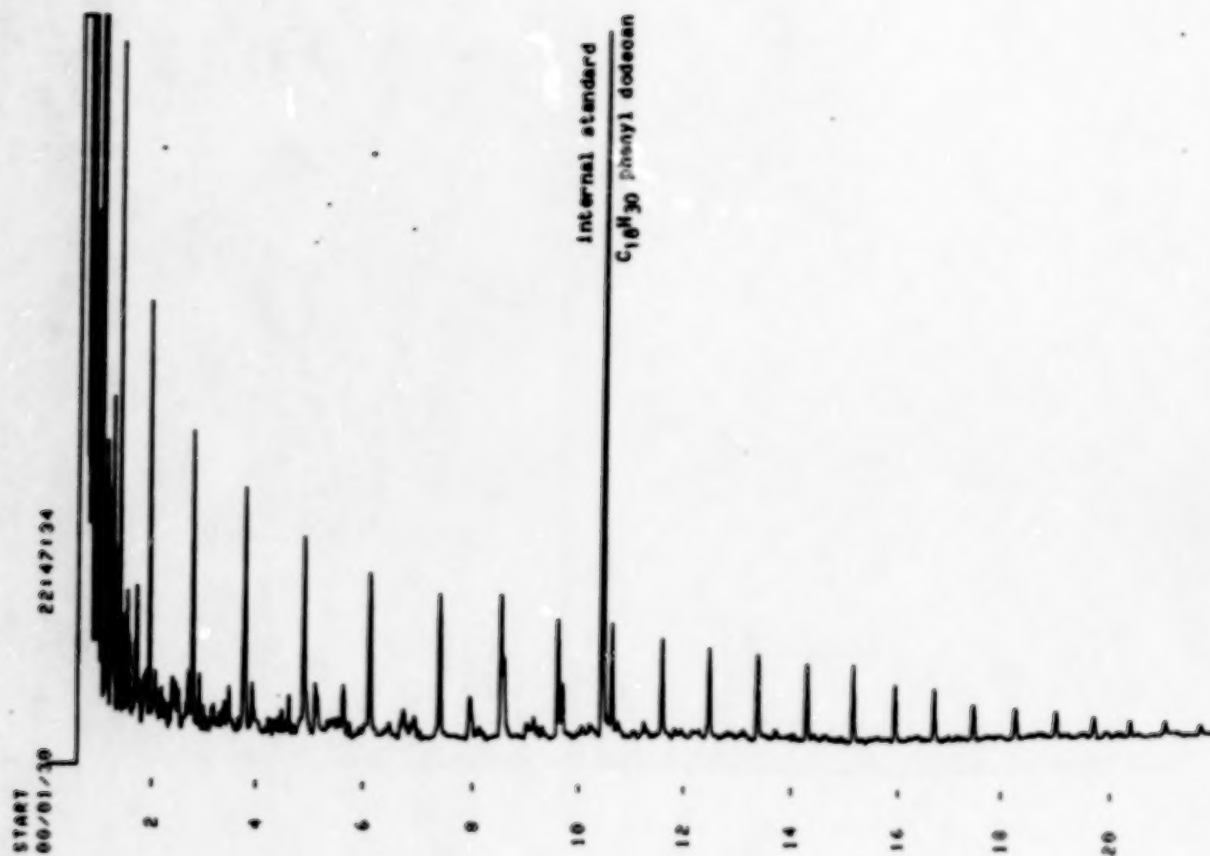


FIGURE A.23 Gas chromatogram of PB₀ oil

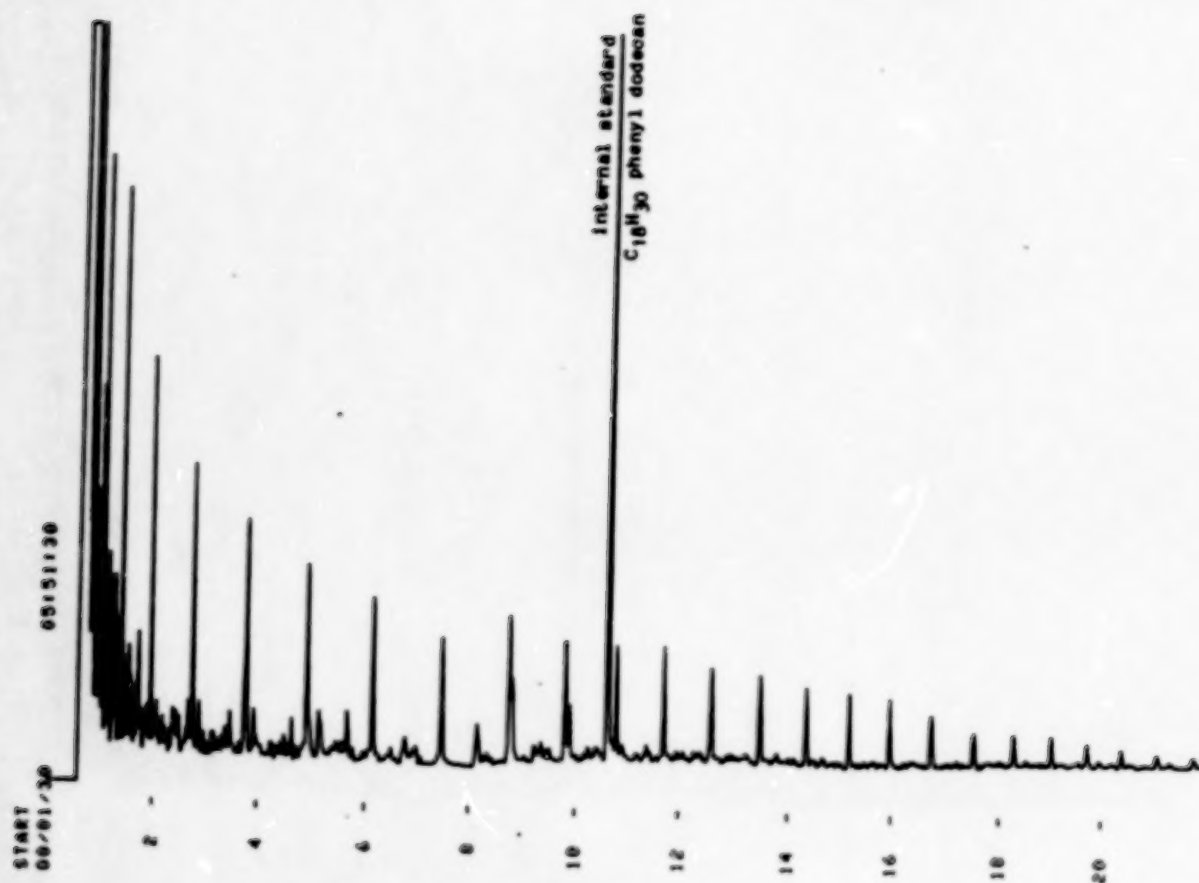


FIGURE A.24 Gas chromatogram of PB₃ oil

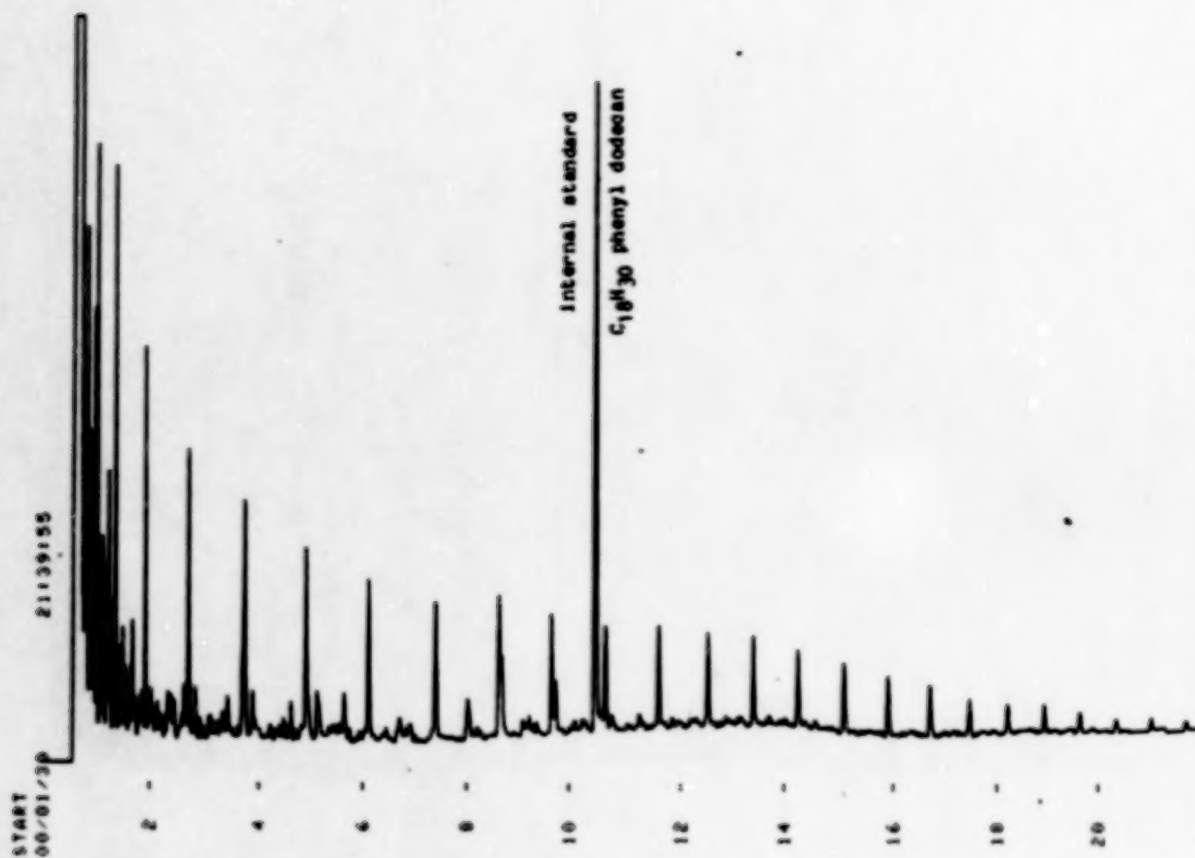


FIGURE A.25 Gas chromatogram of PB₁₀ oil

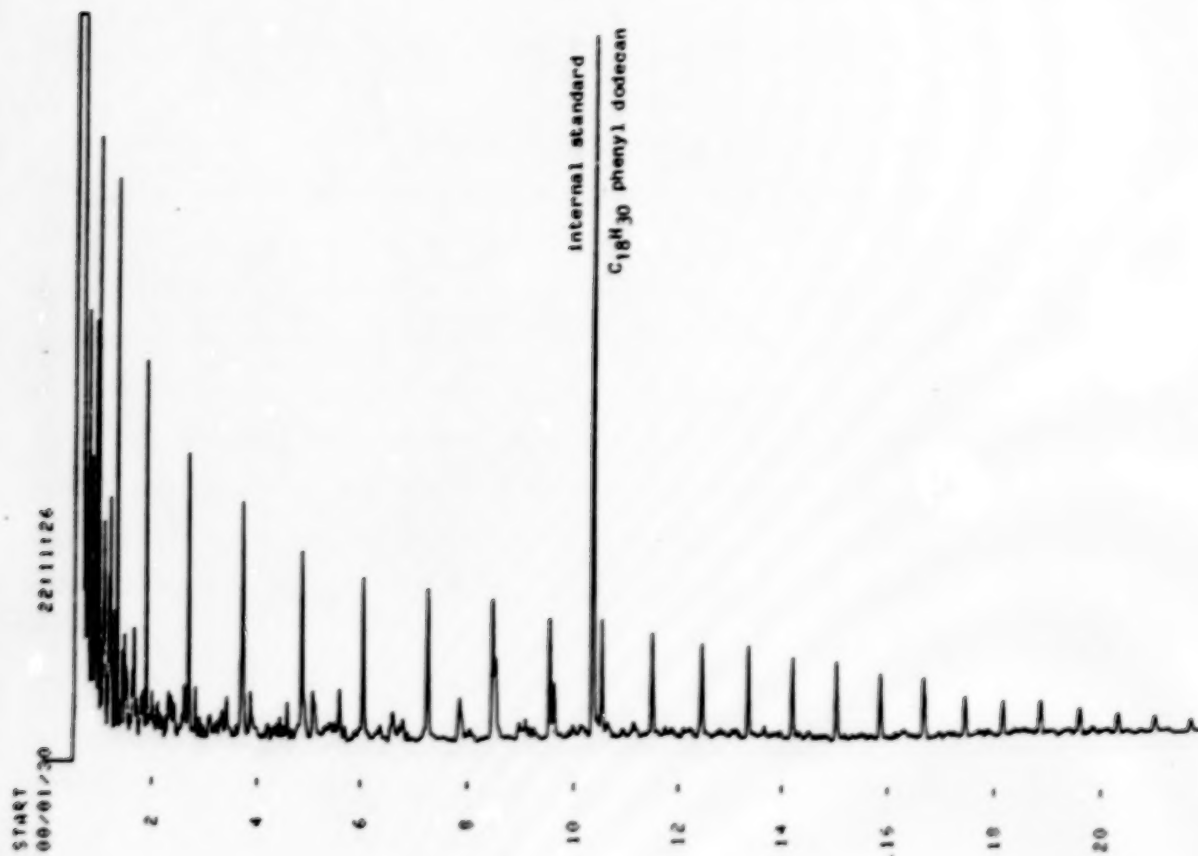


FIGURE A. 26 Gas chromatogram of PB_{36} oil

Preparation of the samples

Water samples including oil droplets, SPM and oiled SPM, were removed from the grid column and collected in 1 litre separatory funnels (Figure IV.6a) or sedimentation columns (Figure IV.6b). The samples were maintained in a stationary position for about 20 hours to separate the samples in three phases (see Figure IV.6):

- a) phase I, surface layer, consisting mainly of oil
- b) phase II, oil and SPM still in suspension
- c) phase III, sedimented matter, consisting mainly of silt.

Phase II was removed from the sedimentation column through the nozzle and poured into an extraction beaker. A polyester membrane filter, with 0.4 μ m pore size (from Nuclepore Corporation) was placed in the beaker. Vacuum-filtration separated phase II in the filtrate and the oil-silt mass on the filter. The filtrate, with dissolved oil compounds and probably very small oil droplets and silt particles, was not analyzed and thrown away. The oil on the filter was recovered by vacuum-filtration with 10 ml methanol and two times 15 ml methylene chloride successively. Oil mass and oil composition were analyzed with FID-GC. The silt on the filter was cleaned by vacuum-filtration with 10 ml distilled water. The silt was dried and weighed.

Phase III was removed from the sedimentation column by a pipette and poured into the extraction beaker. The further procedure was similar to phase II (oil recovery was performed with 15 ml methanol and 2 x 30 ml methylene chloride). The weight and composition of the oil was measured by FID-GC, and the mass of silt by weighing.

The oil in phase I was removed by shaking the sedimentation column with the remaining matter with methanol and methylene chloride successively, and poured directly in a 100 ml sample bottle.

All (three) oil samples from phase I, phase II and phase III were collected in 100 ml sample bottles before GC analysis. The bottle mouth was

covered with aluminum sheet and carefully closed.

A.3 Oil Characteristics

A.3.1 Measurement techniques

Oil density ρ_o

The density of oil, ρ_o , was measured by pycnometers or by weighing.

Oil viscosity ν_o

The measurement of oil viscosity, ν_o , at different temperatures was performed with a Haake Rotovisco RV 100 in combination with the CV 100 measuring system or the M1500 measuring system. Oil temperatures between 5 and 95 °C could be applied. The viscosity range of the apparatus is 0.5×10^{-6} to $10^{-1} \text{ m}^2/\text{s}$ (= 0.5 to 10^5 cSt).

Many high-viscous oil types and emulsified oils are non-newtonian liquids. The rotoviscometer characterizes non-newtonian oil by shear rate versus shear stress viscosity curves, see Figure A.27.

Surface tension and interfacial tension

The oil surface tension, σ_o , and the oil-water interfacial tension, σ_{ow} , was measured with a Krüss K8600 tensiometer by the ring method of Lecomte du Nuoy. A platinum-iridium wire ring was used.

Oil composition

The gross chemical composition of oil samples was determined by gas-chromatography. A Carlo Erba glass capillary gaschromatograph in combination with an ECD detector and a flame ionization detector (FID) was used, in conjunction with the data analysis systems of Hewlett Packard and Shimadzu.

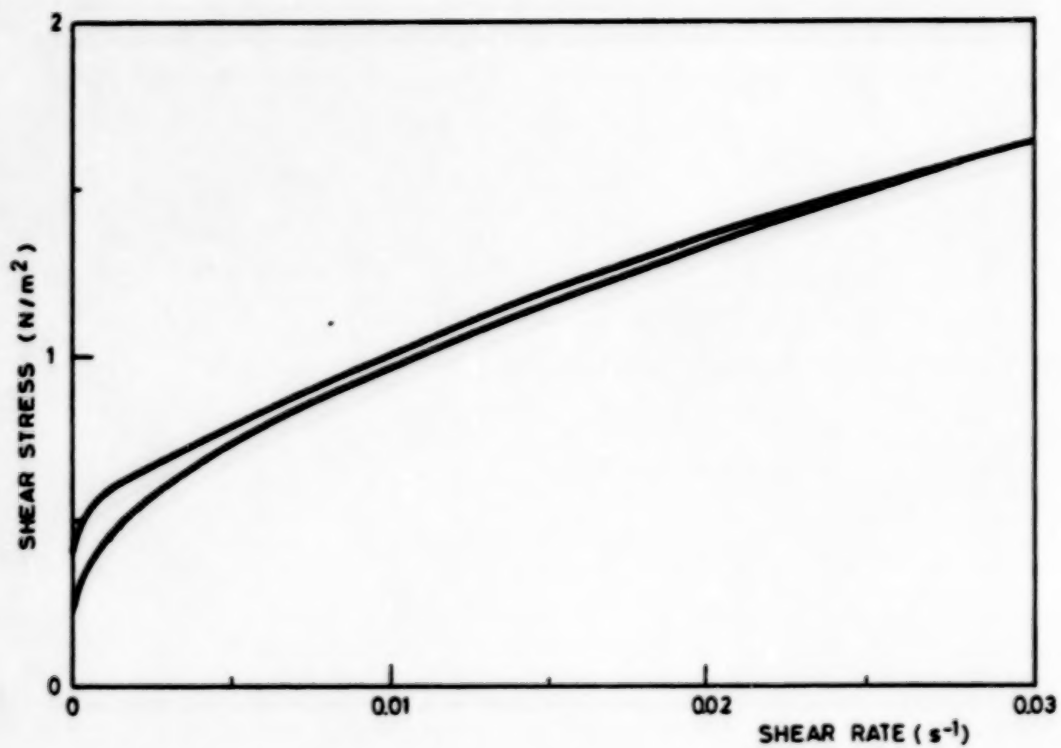


FIGURE A. 27 Viscosity curve of emulsified Prudhoe Bay oil
(PB_{em}, non-newtonian behaviour)

Oil concentration in samples

The determination of the oil composition in a sample by gaschromatography leads also to the concentration of oil in the oil-water sample. If the oil composition was not determined, the oil concentrations were measured with a MIRAM-1A Infra-Red Analyzer. The oil was extracted and homogenized from the sample with carbon tetrachloride. The infra-red light adsorption in the carbon tetrachloride solvent was compared with the adsorption in a set of standard concentration samples with the same type of oil.

A.3.2. Prudhoe Bay and Ekofisk oil, unweathered and weathered

The following types of oil, including different weathering states, were applied in the experiments:

- a) Ekofisk crude oil. Only fresh oil was applied in the experiments. The physical properties are given in Table A.1 by means of the density ρ_o , viscosity ν_o , surface tension σ_o and oil-water interfacial tension σ_{ow} .

The chemical composition is shown in the FID-GC chromatogram in Figure A.22. The chromatogram shows the total concentration of hydrocarbons with the specific carbon number.

Ekofisk oil is generally abbreviated by Eko.

- b) Prudhoe Bay crude oil, unweathered oil as well as weathered oil and emulsified oil was applied in the experiments.

PB₀ indicates Prudhoe Bay unweathered oil. The physical properties are given in Table A.1; the total hydrocarbon composition is given in the gaschromatogram in Figure A.23.

PB₃, PB₁₀ and PB₃₆ indicate Prudhoe Bay oil weathered by evaporation of the volatile components during three, ten and thirty-six days respectively. The oil was spread in shallow dishes with an oil layer thickness of 25 millimetres. The evaporation took place outdoor at a mean temperature of about 6 °C. It is emphasized that "field-weathered"

Table A.1 Physical properties of oil and water

Oil type and weathering state	viscosity ν_o ($10^{-6} \text{ m}^2/\text{s}$, cSt)			surface tension σ_o, σ_w (N/m) (at 20°C)	Interfacial tension (oil-salt water) σ_{ow} (N/m) (at 20°C)	density ρ_o, ρ_w (kg/m^3) (at 20°C)
	20 °C	12°C	4°C			
fresh water				0.0723		1000
salt water				0.0550		1025
Ekofisk	8.0	10.4	12.3	0.0259	0.0187	808
PB ₀	92	124	233	0.0299	0.0300	900
PB ₃	122			0.0305	0.0285	902
PB ₁₀	220			0.0312	0.0261	914
PB _{em}	56000 at shear rate 0.03 s^{-1} (non - Newtonian, see Figure A.27)					992

ring" of PB oil on the sea surface may lead to quite different quantitative and qualitative results as far as the physical and chemical properties are concerned. In field conditions, evaporation will be generally more rapid because of a thinner oil layer generally in the order of magnitude of 1 millimetre. Consequently, few hours of field evaporation with a thin oil film may be similar with the 7 day and 10 day evaporation with the thick layer. Other differences between the weathering of oil layers in the dishes and on the sea surface concern the dissolution of soluble components, photo-oxidation and emulsification that might occur with oil on the sea surface. (Emulsified oil is described in Section A.3.3).

The relative volume loss V_{evap} of laboratory weathered PB oil with respect to unweathered oil is quite small, and is given by:

PB₃: V_{evap} = 4.3 percent

PB₁₀: V_{evap} = 7.3 percent

PB₃₆: V_{evap} = unknown.

In spite of the small volume loss for weathered PB oil, the oil viscosity increases considerably with weathering. The physical properties of PB₃ and PB₁₀ are given in Table A.1, the gas-chromatograms of PB₃, PB₁₀ and PB₃₆ in the Figures A.24, A.25 and A.26. (Weathered-oil experiments were performed only with PB₃ and PB₁₀, the chromatogram of PB₃₆ is given for completeness). The gaschromatograms show a slight decrease of the low alkanes in the oil sample with increasing evaporation, in good agreement with the mentioned small volume loss during evaporation.

A.3.3 Emulsified oil

The series of experiments in the grid column on the effect of turbulence on the oil droplet size distribution contained some experiments with emulsified Prudhoe Bay oil. (See Section III). The reason for the performance of experiments with emulsified oil was the observation of rapid emulsification of PB oil during preliminary tests in the Oil Flume due to the passage of breaking waves through an oil layer (Section V). It is supposed that rapid emulsification will take place in field conditions as well.



FIGURE A.28 Emulsified PB oil in the Delta Flume after a breaking-wave experiment

Indeed, the experiments in the large-scale Delta Flume showed a considerable emulsification of PB oil even after passage of a single breaking wave. The emulsified oil slick is shown in Figure A.28. Visually noticeable emulsification did not occur with Ekofisk oil in the Oil Flume and in the Delta Flume.

PB_{em} indicates the laboratory-made oil-in-water emulsion from fresh Prudhoe Bay oil and salt water ($\rho_w = 1025 \text{ kg/m}^3$, $S = 30 \text{ }^\circ/\text{oo}$). PB_{em} was prepared by slowly adding water to oil, the latter severely stirred by a high-speed impeller. The ultimate oil-water slick contained 75 percent of water. The physical properties are given in Table A.1. PB_{em} appeared a non-newtonian liquid, like the most high viscosity oils and oil emulsions. The viscosity ν_o , defined as the ratio $\nu_o = \text{shear stress/shear rate}$, depends on the shear rate. The shear stress versus shear rate curve is given in Figure A.27. Moreover, PB_{em} appeared a thixotropic liquid with the shape of the curve depending on whether the shear stress was measured with increasing shear rate (upper curve) or with decreasing shear rate, see Figure A.27.

A.4 Particle Collision Probabilities between Particles in Laboratory Vessels and Sample Cells

Collisions between particles might influence the processes investigated in this study. Collisions between oil droplets may lead to coalescence, between silt particles to flocculation, and oil droplet-silt particle collisions may lead to the formation of oil-SPM agglomerates. Evidently, particle colliding is the major process in the oil-SPM interaction phenomenon as it was experimentally investigated in the grid column (Section IV). On the other hand, particle collisions in the sample cells might distort the particle size distribution that occurred in the laboratory vessel at the time of sampling. The oil droplet collisions and subsequent coalescence of the droplets during or after the oil break-up process in the laboratory vessels before sampling may be considered to be a portion of the processes to be investigated.

Estimates are made in this Section on the probability of particle collisions in different conditions, in particular as regards the sample cells where particle collisions may cause undesirable disturbances of the phenomena to be investigated.

The relative transport and subsequent collision probability of particles can be due to Brownian motion, shear caused by turbulence and velocity gradients in the water, and different fall or rise velocities (differential settling). (See, e.g., Interim Report 1986, Hunt 1982). Collisions in the non-turbulent and stagnant conditions in the sample cells are due only to Brownian motion and differential settling.

Smoluchowski (1917) derived the following collision functions for spherical, inertial particles with density ρ_{os} and diameters d_i and d_j . Brownian motion:

$$\beta_B = \frac{2 k T}{3 \mu} \frac{(d_i + d_j)^2}{d_i d_j} \quad (A.2)$$

Differential settling:

$$\beta_{DS} = \frac{\pi g |\rho_w - \rho_{os}|}{72 \mu} (d_i + d_j)^2 |d_i^2 - d_j^2| \quad (A.3)$$

where ρ_{os} = density of the particles (either oil droplets or silt particles), in kg/m^3

d_i, d_j = particle diameters, in m

T = temperature, in K

k = Boltzmann constant = 1.38×10^{-23} J/K

The relative collision probability due to differential settling over Brownian motion is therefore:

$$\beta_{DS}/\beta_B = \frac{\pi g |\rho_w - \rho_{os}|}{48 k T} |d_i^2 - d_j^2| d_i d_j \quad (A.4)$$

Substitution of π (= 3.14), g (= 9.81), k (= 1.38×10^{-23}) and T (= 290 K) leads to:

$$\beta_{DS} / \beta_B = 0.016 |\rho_w - \rho_{os}| |d_i^2 - d_j^2| d_i d_j \quad (A.5)$$

with $|\rho_w - \rho_{os}|$ in kg/m^3 and d_i, d_j in μm

With respect to oil droplets, Equation (A.5) indicates that the collision probability due to Brownian motion is small compared with the probability due to "differential settling" (differential surfacing), even for the smallest values of $|\rho_w - \rho_o|$ and the smallest oil droplet size class that was observed with visual microscopy. Substitution of $\rho_w - \rho_o = 100$ (for PB oil) and $d_o = 3 \mu\text{m}$ results in:

$$\beta_{DS} / \beta_B = 14.4 |d_i^2 - d_j^2| \quad (A.6)$$

The contribution of the Brownian motion to the relative collision probability is only significant if the two droplets considered have a diameter difference much less than $1 \mu\text{m}$. The probability of finding two droplets with this small diameter difference in each others neighbourhood in an empirical condition with a generally wide range of droplet sizes is very small. Consequently, Equation (A.6) leads to the conclusion that in a sample cell the probability of oil droplet collisions due to Brownian motion is negligible relative to differential settling.

It is easy to estimate, without making any calculations, that distortion of the droplet size distribution from coalescence of droplets after collision (due to differential settling) in the sample cells is negligible in the actual experimental conditions. The following features were considered:

- a) volume and shape of the sample cells used were chosen in such a way that the surface fraction covered by the resurfaced droplets (after a stationary period) is not more than few percent.
- b) the droplet sizes in dispersed oil samples are distributed according to Equation (VII.2) over a wide range, with a sharp increasing number of droplets with decreasing diameter.

Section a) indicates that the collision probability from differential settling is small for droplets with diameters of the same order of magni-

tude. Some collisions may take place between large droplets (e.g., $d_o = 100 \mu\text{m}$) and very small droplets (e.g., $d_o = 5 \mu\text{m}$) during the large droplet rise to the surface. Section b) indicates that distortion of the size distribution is only considerable if coalescence occurs by droplets with sizes in the same order of magnitude: the example of the few large droplets coagulating with very small droplets does not considerably increase the size of the large droplet nor reduce considerably the number of small droplets. Consequently, the sample cells used for observation of droplet size distributions in the experiments (Section III, V and VI) were safe as regards the distortion of the distribution by coalescing droplets.

A completely different situation occurs with the oil-SPM samples. (See Section III). Typical SPM concentrations are in the order of 20 ppm (by volume), while a considerable amount of the silt consists of particles with sizes in the order of magnitude of $d_s = 2 \mu\text{m}$. The sample bottles and separatory funnels were about 0.2 m high. This means that a homogeneous settling of the silt particles would cover the bottom completely, and many collisions are to be expected during settling, especially between the (rising) oil droplets and the (falling) silt particles. To guarantee negligible oil-SPM collisions in the sample cells requires a reduction of the SPM concentration in the laboratory facility or the cell height by, say, a factor of 100. The pursued measuring procedure did not permit a workable reduction of one of these parameters and still collect enough matter for (chemical) analysis.

A.5 Quality Assurance Procedure

Project organization

The project undertaken by EHI/Delft Hydraulics Laboratory was subject to the overall direction of the president/manager of EHI and the director of the Estuaries and Seas Division of Delft Hydraulics. The interim report and final report were subject to their approval.

Technical approach, set-up of test program and test procedures were the responsibility of the principal investigator. Control and approval of technical approach, test program and test procedures by the Head Research and Development of the Estuaries and Seas Division of Delft Hydraulics was mandatory.

Day-to-day execution of the project, data collection and record analysis were assigned to a project engineer and project technicians. The supervisor of the workshop supported the project team in design of the test stands.

Project records

Project records were kept in:

- a) Correspondence files. Incoming correspondence was dated and routed for review and initialing. All attachments or enclosures remain in the correspondence files except photographs and plans. Outgoing correspondence was assigned sequential numbers and a list of all outgoing correspondence is kept in the Project Engineer's work book.
- b) Memo files. Project related meetings and phone conversations were recorded on standard sheets.
- c) Plan and data files. Incoming plans and data were dated the day received. A list of plan numbers is kept in the Engineer's work books. Plans were filed in a drawer.
- d) Engineer's Work Book. Binders were used for keeping all test programs, procedures, schedules, correspondence lists, plan lists, calculations, dimensional checks and draft reports.
- e) Project Technician Work Books. Binders were used for keeping only current approved model drawings, test programs and procedures, plus data, data analysis and photographic records. All files, work books and plans are bound together upon completion of the project and placed in storage.

Physical Models - Design, Construction, Testing Programs and Procedures

All model design calculations and other calculations as required followed standard procedures and were initiated by the Project Engineer, performed by engineering of technical staff and reviewed and approved by the Principal Investigator.

Model construction drawing were prepared by engineering or technical staff according to standard procedures, checked by the Project Engineer or another designated engineer and issued for approval by the Principal Investigator.

Model construction was supervised by the Shop Supervisor and Project Engineer. Model dimensions were checked independently of the person responsible for construction. The principal checker was the Project Engineer or a technician designated by him. A dated record of dimensional checks is kept in the Engineers' work book, initialled by the checker. Any deviation between the approved model design and the model as constructed was to be noted and any required action taken. Action was to be initiated by the project engineer, and approved by the Principal Investigator.

Test programs were initiated by the Project Engineer and approved by the Principal Investigator and Head Research and Development. The test program identified the objective of each phase and/or series of tests and identified each test with a number. If, as a result of test results, or other information, modification was considered necessary to test a program, a revised test program was forwarded for approval following the above procedure.

The test procedure for the operation of a model was prepared in writing by the Project Engineer subject to approval by the Principal Investigator and Head Research and Development. The test procedure was initialled by the Project Engineer, Principal Investigator and Head R & D., and kept in the Engineers' work books. Revisions to the test procedure were approved by the Principal Investigator and Head R & D. The approved revision was

initialled, dated, and kept in the Project Technician's work books. The Project Engineer was responsible for issue of only approved current procedures to the Project Technician for use on the model following the same procedure used for control of drawing prints.

Data collection was under supervision of the Project Engineer. Data were recorded and reduced on data sheets which note the project number, run number, data, test flows, items measured and identification number.

Data were analyzed to examine trends and consistency of results. Data obtained by the Technician were checked by the Project Engineer, and vice versa. Data sheets were approved and signed by the Project Engineer and kept in the Project Technician's work books.

A photographic log was kept in the Project Technician's work books noting film number, test number and date of exposure. Prints and negatives were kept in the Project Technician's work books.

Instrumentation

Measuring devices were calibrated prior to commencing the test program. Calibrations of all instruments were recorded.

Measuring and test equipment were of the proper range, type and accuracy. The procedures for using and calibrating specific items of instrumentation required for a project were prepared by the Project Engineer and approved by the Principal Investigator. The Project Engineer was responsible for issue of only current approved procedures to the Project Technicians for use on the model following the same procedure used for control of drawings.

For the particle size analyses no direct calibration was possible. The concentration meters for oil and sediment were calibrated for each different type of oil prior to the relevant tests series, including temperature sensitivity. The gaschromatograph analyses was calibrated according

to the manufacturer's standards and procedures.

Reports

A draft report was prepared by the Principal Investigator following an outline approved by the Project Manager, and Head Research and Development and the Client. The draft report shall be reviewed by the Project Manager and revision undertaken by the Principal Investigator as directed. Transferral of data from work books, or calculation sheets, to graphs and drawing shall be checked and initialled by the Principal Investigator.

Reports were approved by the Project Manager and the Director.

APPENDIX B. SCIENTIFIC PAPER AND SYMPOSIA CONTRIBUTIONS

Two papers on this study were submitted to symposia before completion of the final report:

G.A.L. Delvigne: "Droplet size distribution of naturally dispersed oil". Pp. 29-40 in "Fate and Effects of Oil in Marine Ecosystems" (Proceedings of the IAWPRC-TNO Conference on Oil Pollution, February 1987. Eds. J. Kuiper and W.J. Van Den Brink. Martinus Nijhoff Publishers, Dordrecht, The Netherlands (1987).

G.A.L. Delvigne: "Measurements on natural dispersion". ASTM Symposium on Dispersants: New Ecological Approach through the 90's, October 1987, Williamsburg, Virginia, U.S.A. (Proceedings to be published).

The following journal paper, given on the next pages, was completed at the same time as the final report, and submitted for publication to Oil and Chemical Pollution in December 1987:

G.A.L. Delvigne and C.E. Sweeney: "Natural dispersion of oil". Submitted to Oil and Chemical Pollution, Graham and Trotman Ltd., London (1987).

Natural Dispersion of Oil

G.A.L. Delvigne¹ and C.E. Sweeney²

¹ Delft Hydraulics, P.O. Box 177, 2600 MH Delft, The Netherlands

² Engineering Hydraulics Inc., 14715 NE 95th Street, Redmond, Washington

Laboratory investigations were performed on the natural dispersion of surface and submerged oil. Surface oil broke up into droplets and penetrated the water column due to the effect of breaking waves. Submerged oil parcels (submerged spill) broke up into droplets due to turbulence in the ambient water. The experiments on surface oil dispersion led to the following quantitative relations:

- a) an empirical relation for the oil entrainment rate (dispersed oil mass per unit time), as a function of the oil type, oil layer thickness, breaking-wave energy and temperature,
- b) the droplet size distribution as a function of these parameters,
- c) the intrusion depth of oil droplets related to the wave height.

The experiments with submerged oil resulted in relations for the droplet size distribution in dependence of various parameters.

The empirical relations are applicable in mathematical models for calculation of natural dispersion of oil in the sea, with given hydrodynamic conditions and breaking wave statistics.

1. Introduction

The purpose of this study on natural dispersion of oil was to provide equations for calculating the behaviour of spilt oil in sea conditions using empirical data on the effects of turbulence and breaking waves on oil droplet size, vertical dispersion rate (entrainment) and the resulting oil concentration distribution.

The droplet size distribution of dispersed oil is of particular interest with reference to the stability of dispersion. The oil dispersion rate and

the oil concentration and droplet size in the seawater are important, for example, to the reduction or disappearance of the surface oil, the uptake of oil by marine life and the adsorption of oil by suspended particulate matter and its subsequent sedimentation onto the sea floor. In spite of its importance, relatively little research has been performed on the natural dispersion of oil. Previous investigations were carried out by Aravamudan et al. (1982), Bouwmeester and Wallace (1986), Delvigne (1985), Forrester (1971), Johansen and Audunson (1982), Milgram et al. (1978), Nilsen et al. (1985) and Raj (1977).

The laboratory investigation described here dealt with the following dispersion processes:

- a) break-up of surface oil films into droplets and penetration into the water column due to breaking waves,
- b) break-up of oil parcels from a submerged leak into droplets due to turbulence in the water flow.

The correct modelling of turbulence in laboratory experiments is of major importance. It is well-known that turbulence can be described in terms of eddies of different sizes. The energy of large eddies is transferred via smaller eddies (eddy cascading) to the smallest size class where the energy is dissipated ultimately into heat under the influence of viscosity. The transport of turbulent energy via the eddy cascade leads to identical small-scale eddy structures in different systems if the energy dissipation rates per unit volume, ϵ , are equal. The large velocity gradients of the small eddies are of major importance for the break-up of oil droplets and for the collision probability of droplets whereas the large eddies are primarily responsible for the diffusive transport of the oil droplets. The break-up of coherent surface oil layers into droplets and the intrusion of the droplets into the water column due to breaking waves is a complex of mechanisms in which probably all eddy size classes in the breaking waves play important roles. The need to scale breaking waves, small-scale eddies and large-scale eddies to laboratory conditions is important to the analyses of the mechanisms studied and the scaling of results to field conditions.

Table 1. Physical properties of oil used in the experiments.

oil type, weathering state	viscosity ν_o ($10^{-6} \text{ m}^2/\text{s}$, cSt)			interfacial tension σ_{ow} (N/m, at 20°C)	density ρ_o (kg/m^3 , at 20°C)
	20°C	12°C	4°C		
Ekofisk	8.0	10.4	12.3	0.0187	808
PB ₀	92	124	233	0.0300	900
PB ₃	122			0.0285	902
PB ₁₀	220			0.0261	914
PB _{em}	56000, at shear rate 0.03 s ⁻¹ (non-Newtonian)			992	



Figure 1 Column with oscillating grid

The following three laboratory facilities were used for the experiments:

- a) The "Grid Column" (4 m high, 0.3 m wide, a section is shown in Figure 1). Homogeneous turbulence with different energy levels was generated in a vertical tube by an oscillating grid. The structure of the small turbulent eddies in the column, important to the break-up and coalescence processes, is similar to that found in field conditions and has identical energy levels.

Inlet and/or outlets are situated at different depths in the column. Submerged introduction of oil took place through an inlet near the bottom. In some experiments, oil introduction took place by pouring oil onto the water surface. Samples for oil droplet analysis were withdrawn generally near the middle of the column.

- b) The "Oil Flume" (15 m long, 0.5 m wide, 0.43 m water depth, see Figure 2). The walls and bottom of the flume consist mainly of glass to allow visual observation. Oil surface layers were made by pouring oil onto the water surface. Breaking waves with a wave height in the order of 0.2 m were generated by a wave board. The waves and the turbulence energy levels in these tests were considerably smaller than in field conditions.

- c) The "Delta Flume" (200 m long, 5 m wide, 4.3 m water depth, see Figure 3). The length, width and height dimensions are ten times larger than the dimensions of the Oil Flume. Breaking waves were generated to (almost) field scale by a wave board. The wave heights were in the order of 2 m.

Comprehensive series of measurements were conducted in the relatively easily managed grid column and Oil Flume; a more restricted program was performed in the large Delta Flume. The aim of these measurements was to derive scaling factors for translating the empirical laboratory results into field situations.

The dispersion processes were investigated by varying the following parameters:

- a) oil type and weathering state,
- b) surface film thickness,
- c) turbulence level (breaking wave energy),
- d) water temperature and salinity.

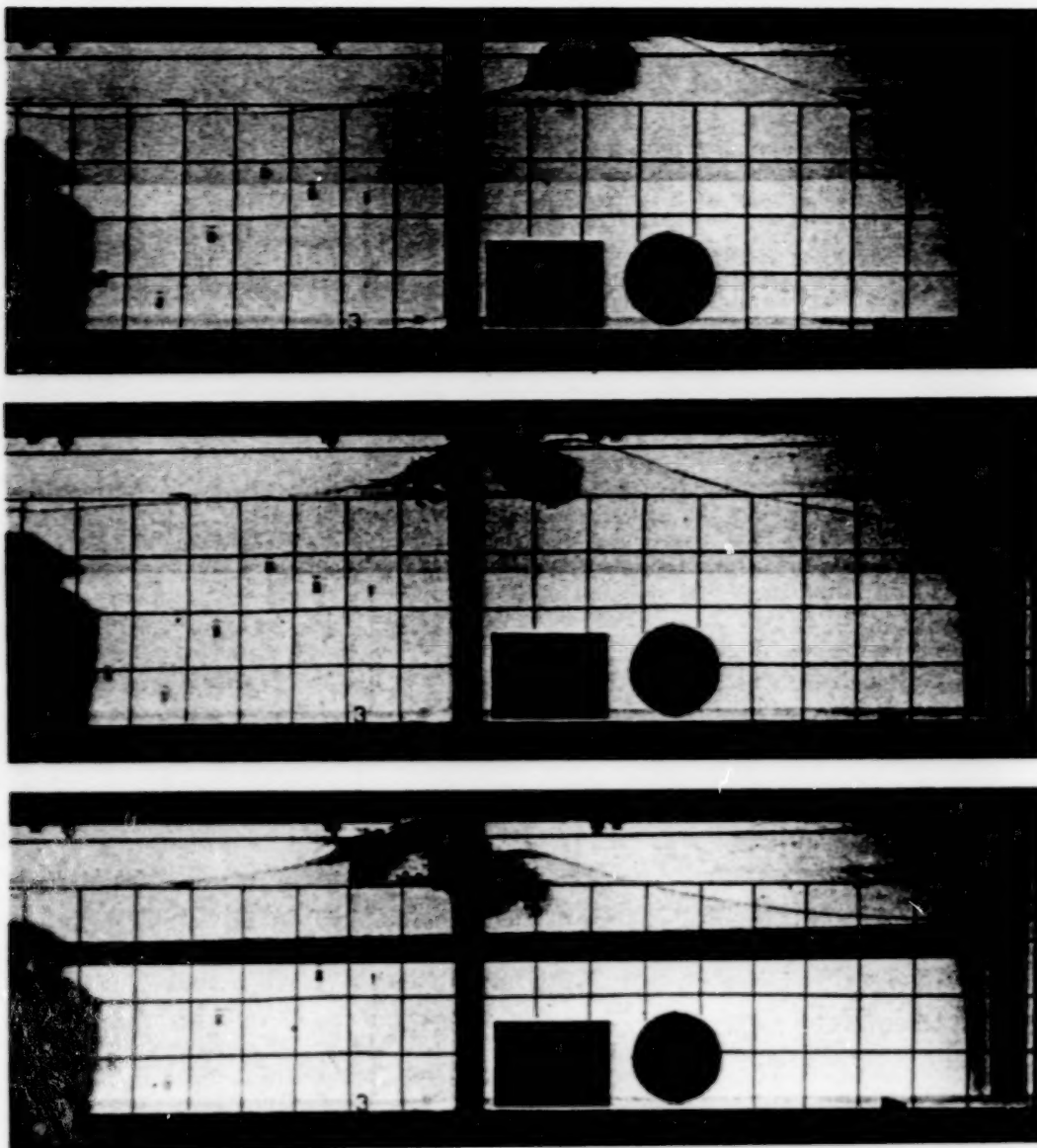


Figure 2 Passage of a breaking wave through an oil slick in the small flume

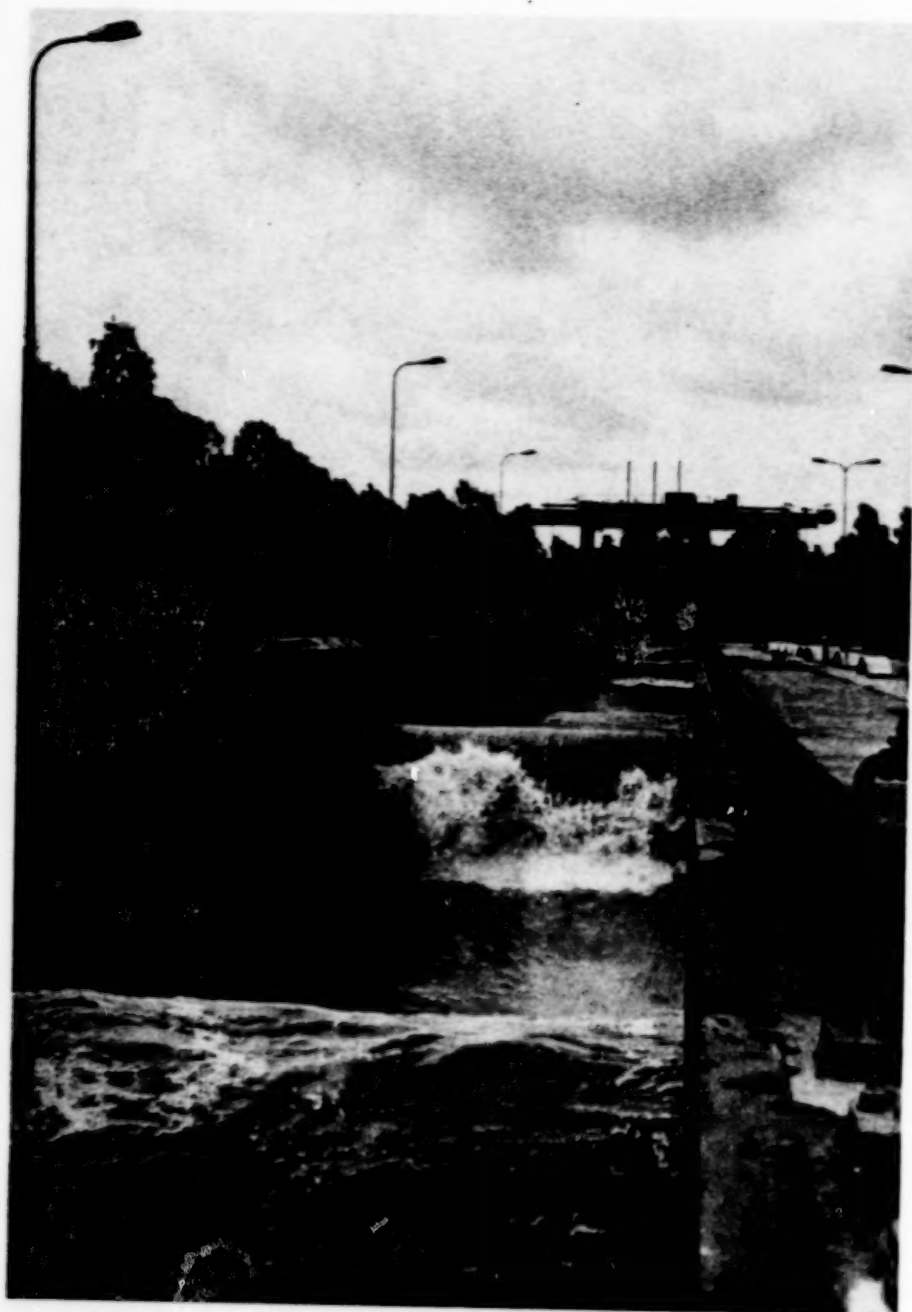


Figure 3 Large flume (Delta Flume)

2. Effect of Turbulence on Oil Droplet Size for Submerged Oil

The effects of different turbulence energy levels and other parameters on the oil droplet size distribution was first investigated by experiments in the grid column. The oscillating grid generates homogeneous turbulence in the column. The structure and energy level of the small-size turbulence eddies, which cause the break-up of oil droplets, are similar in the column and in field conditions if the energy dissipation rates per volume, ϵ ($\text{J/m}^3\text{s}$), are equal. Typical values of ϵ in field conditions are:

deep-sea $\epsilon = 10^{-4}$ to 10^{-2} $\text{J/m}^3\text{s}$

estuary $\epsilon = 10^{-1}$ to 1 $\text{J/m}^3\text{s}$

surface layer $\epsilon = 1$ to 10 $\text{J/m}^3\text{s}$

breaking wave $\epsilon = 10^3$ to 10^4 $\text{J/m}^3\text{s}$.

The value of ϵ in the column can be varied in the range $\epsilon = 0$ to 3.5×10^3 $\text{J/m}^3\text{s}$. This means that experiments on the droplet size distribution in the turbulent conditions in the grid column could be conducted with field values of essential parameters and scaling was not necessary.

Oil droplet size was measured in the column with different conditions of the following parameters:

- a) Prudhoe Bay oil (PB) and Ekofisk oil (Eko) with relatively high and low viscosities respectively. The physical characteristics of the oil types are given in Table 1.
- b) Unweathered PB oil (PB_0), oil weathered by evaporation (PB_3 and PB_{10}), and emulsified oil (PB_{em}). The main effect of evaporation and emulsification is to increase viscosity, see Table 1. (PB_3 and PB_{10} refer to 3 day and 10 day evaporation from an oil layer of 2.5 centimetres thick. The duration of evaporation itself is of minor importance, the same effect on viscosity can take place on a thin oil layer on the sea surface in only few hours).
- c) Turbulence energy dissipation rate per unit volume, ϵ , from 0 to 3500 $\text{J/m}^3\text{s}$. The high energy levels correspond to the energy in breaking waves in field conditions.
- d) Grid oscillation duration $t_{\text{grid}} = 5$ s for simulation of the short-duration turbulence of a breaking wave, and $t_{\text{grid}} = 600$ s to obtain a

steady state droplet size distribution.

- e) Temperature $T = 4, 12$ and 20°C .
- f) Water salinity $S = 0$ ‰ (fresh water), $S = 10$ ‰ (brackish water) and $S = 30$ ‰ (seawater salinity).
- g) Surface oil film and submerged oil parcels.
- h) Oil concentration of 20, 50 and 150 g/m^3 in the column.

The oil was generally introduced into the grid column as large oil droplets (droplet size $d_0 = 10\text{ mm}$) near the bottom. In some tests with high turbulence levels, the oil was introduced at the water surface, the oil being entrained in the water column by the turbulence. The turbulence grid was switched on for a period t_{grid} . Oil-water samples were withdrawn continuously from the grid column and led through a laser-beam particle sizer (LBPS) in order to determine the droplet size distribution in the size range from $d_0 = 11\text{ }\mu\text{m}$ to $d_0 = 1130\text{ }\mu\text{m}$. (Examples of the measured data are shown in Figure 6). In the course of the study it appeared that the measurable droplet size range tended to be greater than about $50\text{ }\mu\text{m}$ due to the dominant contribution of large droplets in the volume of dispersed oil. Smaller droplets were certainly present but were not detected. The measurements with the LBPS were therefore used mainly to determine the influence of various parameters on the mean droplet size, d_{50} , and on the maximum droplet size, d_{max} , in the droplet size distribution $N(d_0)$. Droplets with $d_0 > 1130\text{ }\mu\text{m}$ were detected visually from video recordings through the transparent column wall.

Some of the experimental results are given in Figures 4 and 5. The d_{50} measurements are given in Figure 4 as a function of the oil viscosity ν_0 for different turbulent energies and turbulence durations. The measurements were performed with different oil types, weathering states and temperatures, indicated in the figure by the viscosity ν_0 . The maximum droplet size d_{max} in the measurements on submerged oil is given in Figure 5 as a function of the turbulence energy level e , oil type and turbulence duration t_{grid} . The measurements led to the following conclusions:

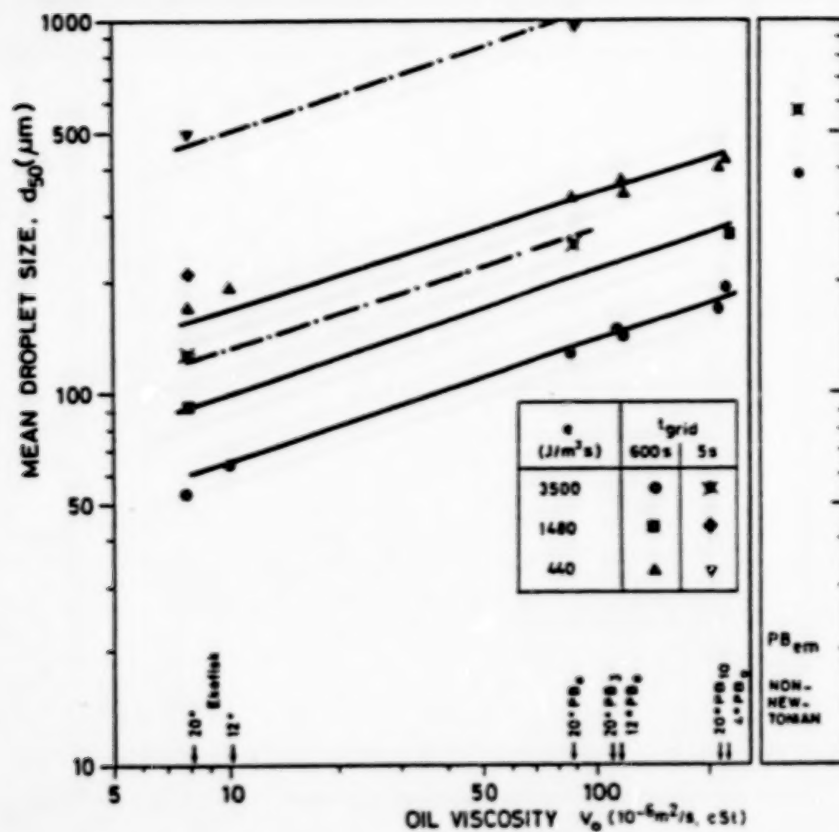


Figure 4 Mean droplet size d_{50} versus oil viscosity v_0 for submerged oil in turbulent ambience with turbulence energies e , and turbulence durations t_{grid} . (Grid column experiments).

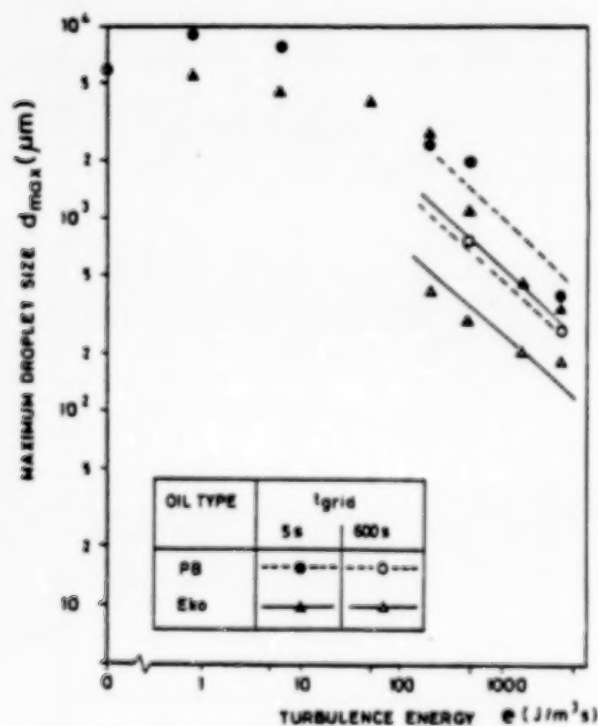


Figure 5 Maximum droplet size d_{max} versus turbulence energy e in experiments on break-up of submerged oil parcels. (Curves according to $d_{max} \sim e^{-0.5}$).

$$a) \quad d_{50}, d_{\max} \sim v_o^{0.34} (\pm 0.05) \quad (1)$$

d_{50} and $d_{\max}$ depend on oil type, weathering state and temperature only as far as these parameters influence the viscosity v_o . The relationship is supported by experiments with oil in the viscosity range from 8 to 220 cSt. Probably, the equation can be extrapolated with some confidence to higher viscosities for newtonian-type oil. The relationship is unsatisfactory for non-newtonian oil types, as can be seen from the measurements on emulsified oil in Figure 4.

$$b) \quad d_{50}, d_{\max} \sim e^{-0.50} (\pm 0.1) \quad (2)$$

Equation (2) is valid in a high-turbulence ambience with $e \geq 100 \text{ J/m}^3 \text{ s}$, where additional break-up due to shear on the rising buoyant droplets is negligible. (The curves in Figure 5 are drawn according to Equation 2).

c) $N(d_o)$ depends on the turbulence duration, t_{grid} . A steady-state droplet size distribution was obtained for $t_{\text{grid}} \geq 5$ minutes, see the example in Figure 6. This implies that the droplet size distribution due to a single breaking wave is not a steady-state distribution.

d) $N(d_o)$ is independent of the water salinity.

e) $N(d_o)$ is independent of how oil is added to the system, that is as a surface oil film, or submerged oil parcels.

Note 1 The steady state mentioned in Conclusion c was apparently not an equilibrium between desintegration and coalescence of droplets, because it was found experimentally that the steady state droplet size distribution was independent of the oil concentration in the column. The stagnating droplet break-up after a certain time may be due to physicochemical changes of the droplets, especially at the oil-water interface, because of the dissolution of soluble components, adsorption of specific compounds from the water

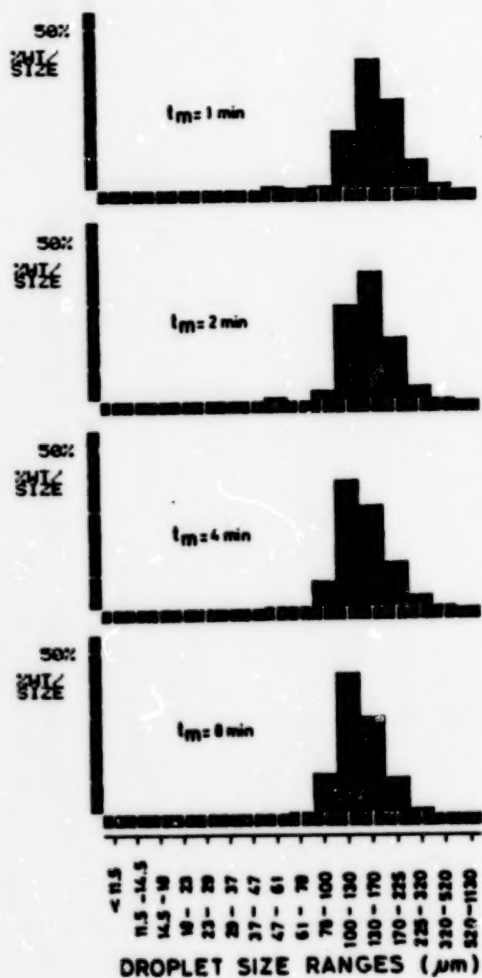


Figure 6

Droplet size distributions at different times t_m after the start of the turbulence. The ordinate indicates the relative oil concentration by volume (%).

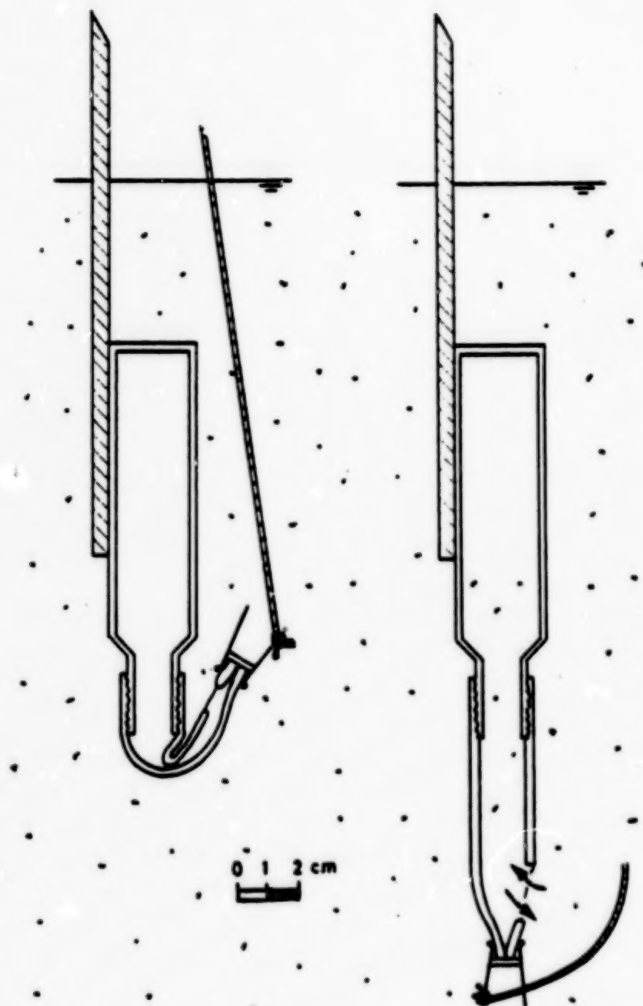


Figure 7

Oil droplet sampler in closed and open position

phase, or migration of specific oil components to the interface.

Note 2 It is very likely that the oil viscosity ν_o and the oil-water inter-facial tension σ_{ow} are important parameters in connection with the break-up of oil droplets. The present measurements were performed with oil types with very little difference in σ_{ow} . Therefore, it was only possible to find a d_o versus ν_o relationship. The effect of σ_{ow} on d_o is shown very clearly by application of chemical dispersants, causing σ_{ow} and d_o to decrease by one or more orders of magnitude.

3. Experiments on Oil Dispersion due to Breaking Waves

The turbulence in the ocean is an important factor in various oil dispersion processes. The initial break-up and submergence of a coherent oil surface slick as well as the secondary break-up of the oil parcels into smaller droplets depends on the turbulence structure, especially near the water surface. In addition, turbulence also plays an important role in the vertical diffusion of oil droplets into the water column.

The turbulence in the surface layer of the sea is generated by overall (tidal) sea currents, wind-drift currents and waves. The wind-drift currents and waves are in turn generated by the wind. It is generally believed that, for a substantial dispersion of surface oil, breaking waves should be present. It is not known, however, if the presence of breaking waves is essential for dispersion to take place in field conditions. Probably, the stretching and contracting of the oil surface layer by waves can lead to some dispersion. However, in the small-scale laboratory experiments non-breaking waves alone did not lead to measurable oil dispersion.

3.1 Small-scale experiments

Experiments were performed in the small-scale "Oil Flume", 15 m long, 0.5 m wide, and with a water depth of 0.43 m. Salt water ($S = 30$ ‰) was

used. The experiments were carried out to study the effect of breaking waves on a surface oil film. The following parameters were measured:

- a) oil entrainment (mass of dispersed oil droplets),
- b) droplet size distribution $N(d_o)$ of dispersed oil droplets,
- c) vertical intrusion of oil droplets in the water mass.

The flume was equipped with a programmed wave generator. Seven wave trains were selected, each one characterized by the specific wave height (in the order of 0.2 m) and energy dissipation of the (single) breaking wave. The wave trains were programmed such that the breaking wave event occurred in the test section at some distance from the wave board. The breaking waves and the generated turbulence energy levels were small compared with field conditions. Therefore, the results of the flume experiments must be scaled into field conditions.

Oil was poured onto the water surface in the test section of the flume. This resulted in an oil film with a thickness of $h_o = 0.5$ mm in most experiments. The entire path of the breaking wave event was located in the flume section covered by the oil film. Figure 2 shows the passage of a breaking wave through the oil layer. The intrusion depth of the oil droplets due to breaking wave turbulence was observed by taking photographs of the oil droplets (or dye sprayed in the water surface) after the wave passage.

The droplet size distributions in these experiments were not obtained with the laser-beam particle sizer because of the limited range of measurement (see Section 2), but with a series of nine samplers. The sampling device, shown in Figure 7, consists of a small glass cylinder (contents 50 cm^3) with a flat top. The cylinder is provided with a flexible silicon tube which is closed when it is bent by pulling on a rope. The sampler is filled with heavy brine. In the open position in the flume, there was flow exchange between the brine in the sampler and the ambient water. (The volume exchanged was subsequently derived by measuring the water density in the sampler). After sampling, the tube was reclosed, taken out of the flume and kept vertical in stationary position for twenty hours. The oil

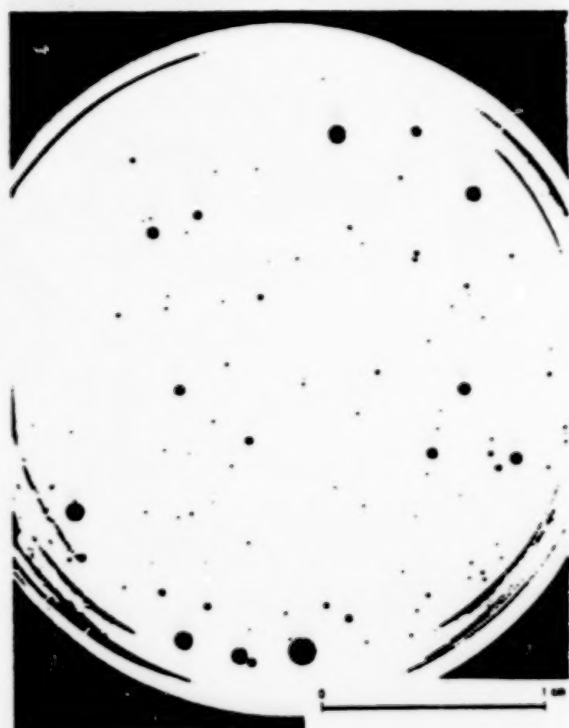
droplets rise to the top of the glass cylinder. Photographs were taken of the top glass to enable the oil droplets to be counted into large size classes with $d_o \geq 100 \mu\text{m}$, see Figure 8a. Droplets with $d_o \leq 100 \mu\text{m}$ were measured and counted by placing the sampling device directly under the microscope. The oil droplets were distinguished from dust particles and air bubbles by using an ultra-violet light source, making use of the fluorescent characteristics of oil in UV light. Figure 8b shows a micrograph picture of a sample. Oil droplets down to $d_o = 3 \mu\text{m}$ could be measured in this way.

Nine samples were removed for microscopic observation during each experiment. These were identified by three depths, and three different times t_m after the passage of the breaking wave. Each sample was withdrawn while the sampler was moving on a carriage along the flume in order to sample while traversing the entire length of the oil droplet cloud: the total amount of oil dispersed by a breaking event could, therefore, be obtained. A moving sampler was also useful for averaging the sometimes irregularly distributed areas of dispersed oil droplets over the length of the flume. An example of this irregular distribution is shown in Figure 2.

The main series of experiments were performed with the following variables (see the summary of experiments given in Table 2):

- a) oil type and weathering state: PB₀, PB₁₀ and Ekofisk
- b) four breaking waves with different energy dissipation
- c) temperature: $T = 2, 8$ and 15°C ,
- d) oil layer thickness: $h_o = 0.2, 0.6$ and 1.2 mm .

Important breaking wave parameters may be, as far as the oil entrainment and oil droplet break-up are concerned, the total length of breaking l_b in the oil slick, the energy dissipation per unit surface area D_{ba} , the energy dissipation rate per unit volume in the breaking wave area e , and the wave height H_b . The length l_b indicates how much surface oil is involved in the dispersion process, D_{ba} is probably important to the oil entrainment, e indicates the energy of the small turbulent eddies and has therefore probably major influence on the break-up of oil droplets and the



a) macrograph

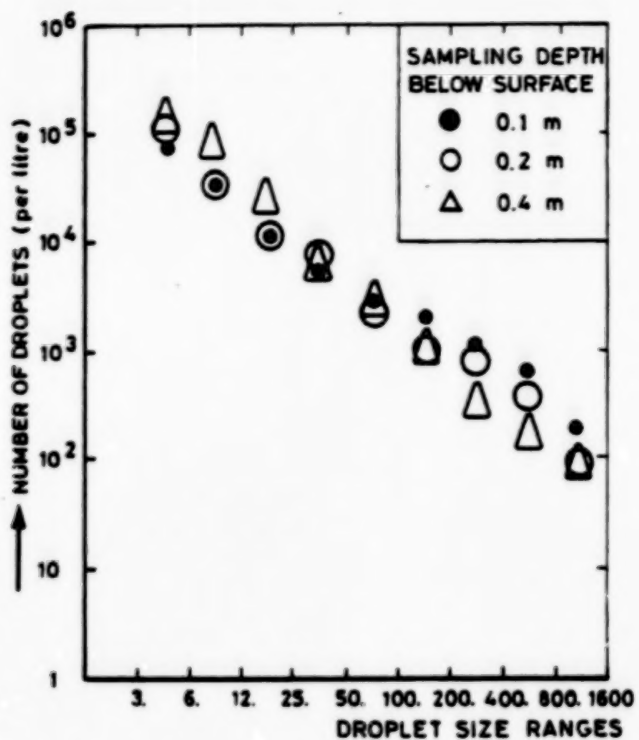
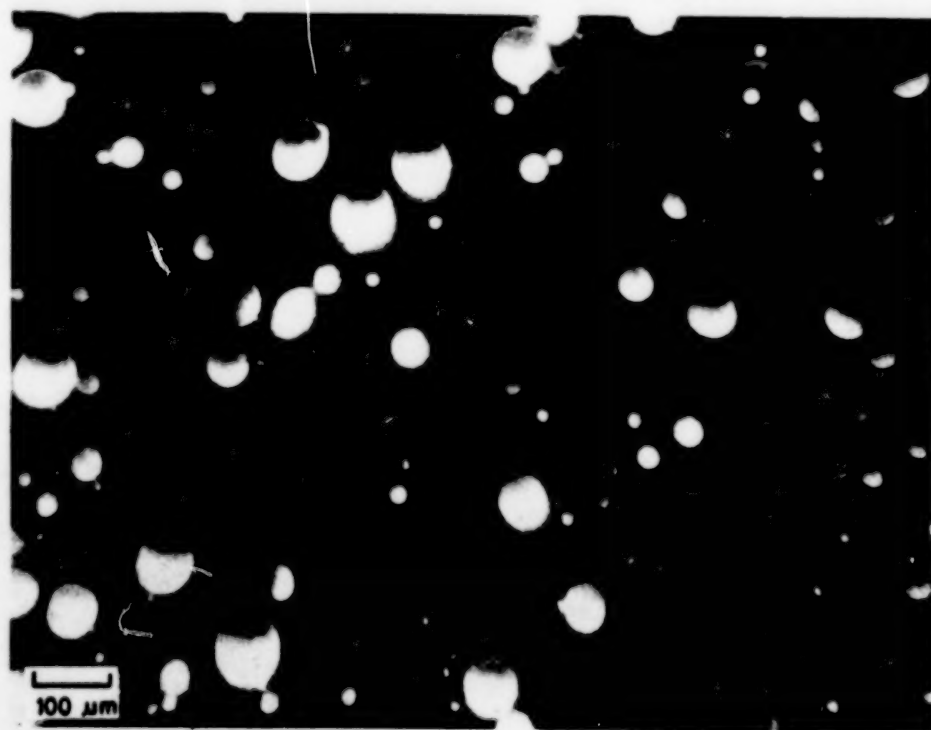


Figure 9 Oil droplet size distributions in breaking wave experiment



b) micrograph

Figure 8 Oil droplets in sample from breaking wave experiment.

droplet sizes, and H_b may indicate the intrusion depth of the oil droplets.

The energy dissipation in a wave train with a single breaker was derived from the energy balance of the breaker zone. Two wave-height meters were placed in the flume, one before and one beyond the breaker zone. The energy dissipation D_{ba} was found by subtracting the time-integrated energy fluxes before and beyond the breaker zone. The length of breaking l_b and the wave height H_b were obtained from photographs taken at intervals of 0.1 s. Results of the wave measurements in the flume are given in Table 2. It was very difficult to determine the values of ϵ in the flume (see Delvigne et al. 1987). The parameter ϵ is important in connection with droplet break-up in the grid column, but it appeared that both the oil entrainment and the droplet size distribution $N(d_o)$ in the flume experiments could be described completely by other breaking wave parameters. No further attention is paid therefore to the influence of ϵ in this paper.

3.2 Large-scale experiments

Some of the small-scale flume experiments were also performed in the large-scale "Delta Flume", with a length scaling factor of $n_l = 10$ relative to the Oil Flume. This means that the water depth was increased from 0.43 to 4.3 m, and the wave height from 0.2 to 2 m. In many respects, the experiments in the large flume can be considered as full-scale experiments.

The large flume was equipped with a wave generator similar to that in the small flume. The wave generator was steered by the same wave train signals, with an amplitude scaling factor of 10 and a wave period scaling factor of $10^{1/2}$ giving a wave length scale of 10. The measurements of wave characteristics were made in a similar way to those made in the small flume. Results are given in Table 2.

Table 2. Measured breaking-wave characteristics

flume	wave	H_b (m)	$\bar{T}_w$ (s)	l_b (m)	D_{ba} (J/m ²)
small flume	2	0.23	1.25	1.83	9
	3	0.24	1.20	1.87	5
	5	0.15	1.00	1.34	2
	7	0.10	0.80	0.72	1
large flume	2	1.9	4.2	21.3	900*
	3	1.8	4.1	15.4	500*
	5	1.4	3.5	10.0	200*

* D_{ba} values for the large flume were obtained by multiplying the measured values in the small flume by the theoretical scaling factor of 100.

Table 3. Summary of flume experiments on oil dispersion due to breaking waves.

Flume	experi- ment	oil type	wave*	layer h_o (mm)	temp. T(°C)	experi- ment	oil type	wave*	layer h_o (mm)	temp. T(°C)
small flume	S2	PB ₀	2	0.6	15	S13	PB ₀	7	0.6	15
	S21	PB ₀	2	0.6	15	S12	Eko	7	0.6	15
	S3	PB ₁₀	2	0.6	15	S17	PB ₀	2	0.6	2
	S4	Eko	2	0.6	15	S18	Eko	2	0.6	2
	S7	PB ₁₀	3	0.6	15	S19	PB ₀	2	0.6	8
	S11	Eko	3	0.6	15	S20	Eko	2	0.6	8
	S14	PB ₀	5	0.6	15	S9	PB ₀	3	0.2	15
	S15	PB ₁₀	5	0.6	15	S8	PB ₀	3	0.6	15
	S16	Eko	5	0.6	15	S10	PB ₀	3	1.2	15
large flume (full- scale)	F2	PB ₀	2	$\bar{h}_o$ (mm) 1	12	F1	PB ₀	5	$\bar{h}_o$ (mm) 1	12
	F3	Eko	2	1	12	F5	Eko	5	1	12
	F4	PB ₀	3	1	12					

* The waves are identified by numbers. The corresponding wave characteristics are given in Table 2.

The experiments were as similar as possible to the small-scale flume experiments. The same droplet sampling system was used for microscopic determination of the droplet size distribution. Other samples were taken from four different depths to determine oil concentration using infrared spectroscopy.

The parameters varied were the type of oil (PB₀ and Ekofisk) and the breaking wave energy, as indicated in Table 3. The mean oil layer thickness $\bar{h}_0$ was about 1 mm since the scaled-up value of $h_0 = 5$ mm was not feasible. (It is shown in Section 4.3 that the oil entrainment and the droplet size distribution are independent of h_0).

4. Results of the Oil Dispersion Experiments

The oil break-up experiments in the grid column, in the small-scale and in the large-scale flumes, led to empirical relationships for oil entrainment Q , droplet size distribution $N(d_0)$, and intrusion depth z_1 .

4.1 Oil droplet size distribution

Figure 9 shows examples of droplet size distributions in three samples taken at the same time but at different depths. (The samples were taken at 0.1, 0.2 and 0.4 m below the water surface in the small flume). The graphs show $N_1(d_0)$ versus d_0 where $N_1(d_0)$ is the number of droplets in the logarithmic droplet size interval $0.5 d_0$ to $1.0 d_0$.

A remarkable result obtained from these data is the linear relationship between $\log N_1(d_0)$ and $\log d_0$ and identical incline of the straight lines through the measurements for all experiments independent of oil type, weathering state, oil layer thickness and temperature. The droplet size distributions in all experiments in the three laboratory facilities, for both surface oil and submerged oil, followed the relationship:

$$N_u(d_0) = d_0^{-2.30 (\pm 0.06)} \quad (3)$$

where $N_u(d_o)$ = number of droplets in a unit size interval d around d_o , e.g., interval $d_o - \frac{1}{2}d$ to $d_o + \frac{1}{2}d$. Equation (3) is equivalent to $N_1(d_o) \sim d_o^{-1.3}$ for the logarithmic intervals $0.5 d_o$ to $1.0 d_o$ as shown in Figure 9.

This distribution is valid in all conditions for droplet sizes down to at least $d_o = 3 \mu m$ (limit of routine measurements). Conditions for the maximum droplet size d_{max} are very different in the grid column and the flume experiments as shown in the following descriptions.

In the grid column experiments all oil droplets were taken into account in the droplet size distribution because the surfacing of large droplets could generally be neglected. This means that all oil introduced in the column was included in $N(d_o)$. Equation (2) describes d_{max} in the grid column experiments in different turbulent conditions: the droplet sizes were smaller in experiments with higher energy dissipation rate ϵ , see also Figure 3. d_{max} was also dependent on the duration of turbulence. Measurements with turbulence durations from $t_m = 5$ s to $t_m = 600$ s indicated that steady-state values of d_{max} in high-turbulent conditions were obtained for $t_m \geq 5$ minutes.

In the flume experiments with breaking waves, the dispersed oil was generally only a small fraction of the total oil mass in the surface slick. Or, to put it in another way, all surface oil was submerged by the breaking wave, but the oil lumps and big oil droplets resurfaced almost immediately after the breaking event. d_{max} decreased with increasing time t_m after the breaking wave passage. It could be concluded from the Oil Flume and Delta Flume experiments that the maximum droplet size d_{max} in the water mass was independent of the break-up processes due to turbulence, but was rather dependent on resurfacing parameters, e.g., intrusion depth z_1 , rise velocity of the oil droplets $W(d_o)$, and vertical turbulent diffusion coefficient ϵ_z .

Equation (3) implies that the following equation holds for the relative volume of dispersed oil as a function of the size classes:

$$V_t(d_o) = 1.45 V(d_o) \quad (4)$$

with $V(d_o)$ = volume of oil droplets in the size interval $0.5 d_o$ to $1.0 d_o$

$V_t(d_o)$ = volume of oil droplets smaller than d_o if Equation (3) is valid down to $d_o = 0$.

Equation (4) indicates a rapid decrease in volume for smaller droplets.

Bouwmeester and Wallace (1986) performed oil dispersion experiments in a small wave flume, resulting in droplet size distributions according to $N_u(d_o) \sim d_o^{-1}$ that should be valid close to the water surface. The range of measurements was from 12 to 2000 μm .

4.2 Oil droplet intrusion depth

Measurements of the intrusion depth of oil droplets due to breaking waves in small-scale and large-scale experiments led to the following average relation (Figure 10):

$$z_1 = (1.50 \pm 0.35) H_b \quad (5)$$

with H_b = height of breaking wave

The oil concentration and the droplet size distribution were almost all the same for all depths within the intrusion depth z_1 for small droplets but decreased with increasing depths for large droplets due to resurfacing. (The homogeneous droplet size distribution and oil concentration over the depth for small droplets, and the inhomogeneity for large droplets, is clearly shown in the example given in Figure 9. The homogeneity over the almost entire intrusion depth implies a sharply defined depth z_1).

Equation (5) agrees well with the Nilsen et al. (1985) conclusion that the empirical intrusion depth is 1.5 to 2 times the breaking wave height.

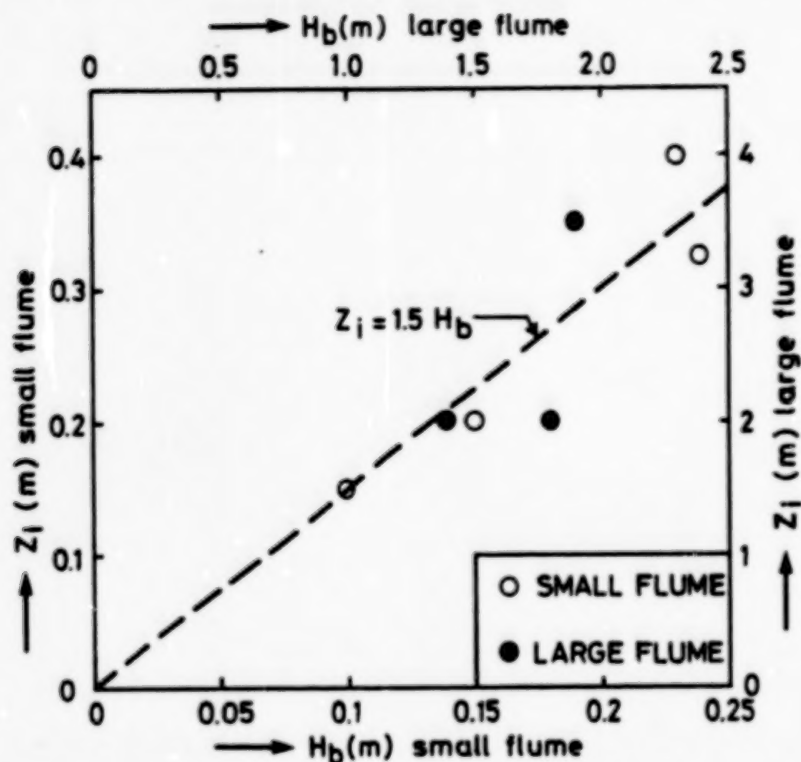


Figure 10 Intrusion depths z_i in the small and large flumes, versus breaking wave height H_b .

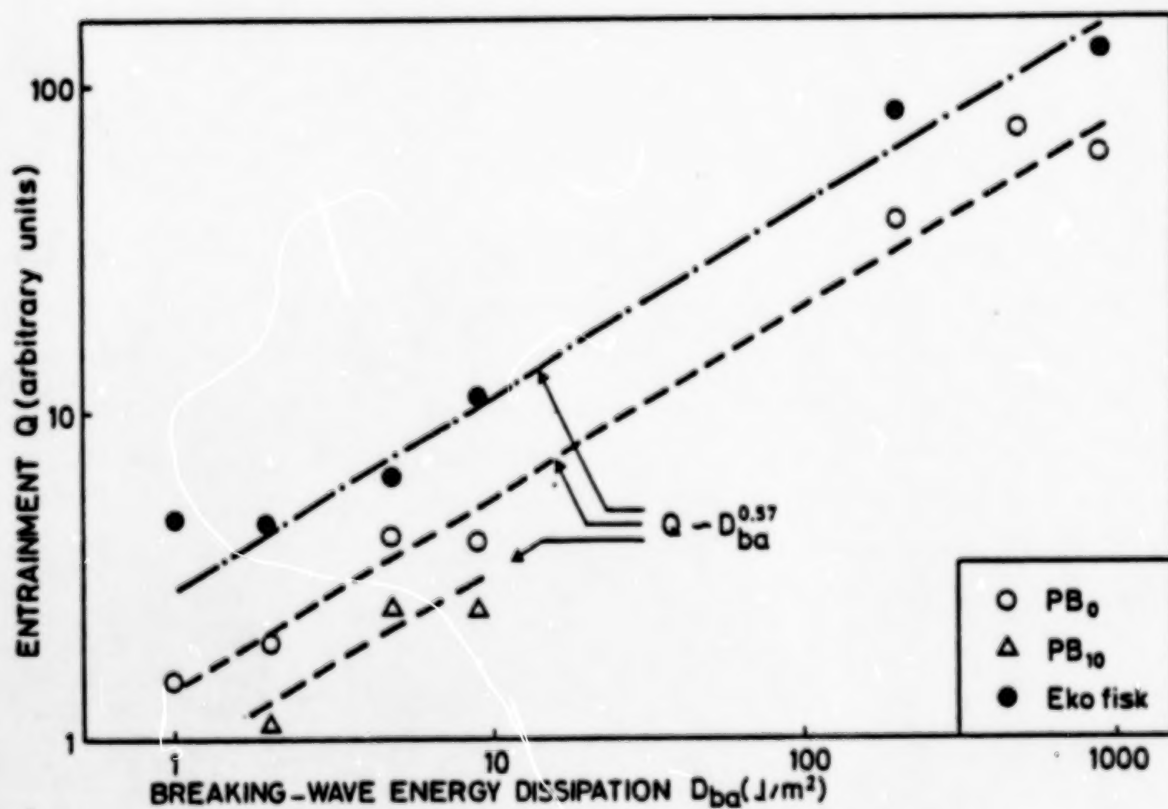


Figure 11 Entrainment Q versus breaking-wave energy dissipation D_{ba} in small-scale ($D_{ba} < 10 J/m^2$) and large-scale ($D_{ba} > 200 J/m^2$) experiments.

4.3 Entrainment of oil

The oil entrainment Q (kg/m^2) is defined as the dispersed oil mass in the water column per unit surface area per breaking event. Because of the resurfacing of large droplets Q depends strongly on the length of time after the passage of the breaking wave.

Empirical results were obtained for oil entrainment for different breaking wave energies, oil types and weathering states (Figure 11), temperatures (Figure 12a), and surface layer thicknesses (Figure 13). The data were derived by fitting the $N_1(d_o)$ versus d_o straight lines of the specific experiments with the general inclination given by Equation (3). Curve-fitting was performed with data for droplet sizes smaller than 200 μm ; these size classes had not been distorted by resurfacing during sampling. The following conclusions were drawn:

a) Entrainment with different breaking waves.

Figure 11 shows the empirical data. The breaking waves are characterized by the dissipated energy per unit surface area D_{ba} (J/m^2). In the small flume D_{ba} ranged from 1 to 9 J/m^2 , and in the large flume from 200 to 900 J/m^2 . The data resulted in the empirical relationships:

$$Q = D_{ba}^{0.57(\pm 0.06)} \quad (6)$$

Equation (6) was valid in both small-scale and large-scale experiments, D_{ba} varying by a factor of 900.

b) Entrainment with different oil types and weathering states.

The data on Q versus D_{ba} for PB_0 , PB_{10} and Ekofisk oil are given in Figure 11. The ratio between the entrainment of Ekofisk and PB_0 appeared to be constant for the different breaking waves in the small flume and the large flume. A constant ratio was also found for PB_0 and PB_{10} , but the experiments with PB_{10} were only performed in the small flume.

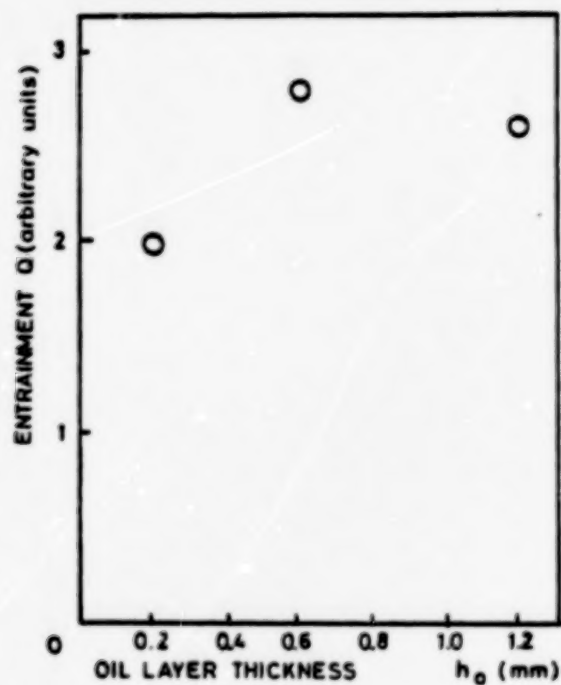
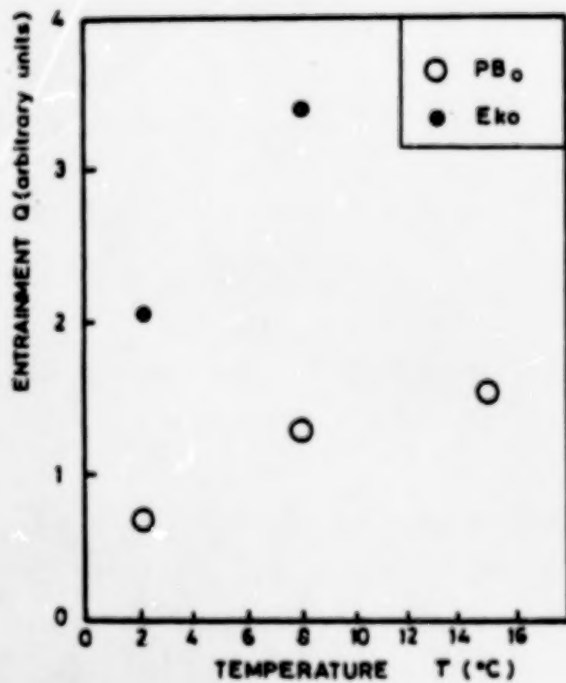
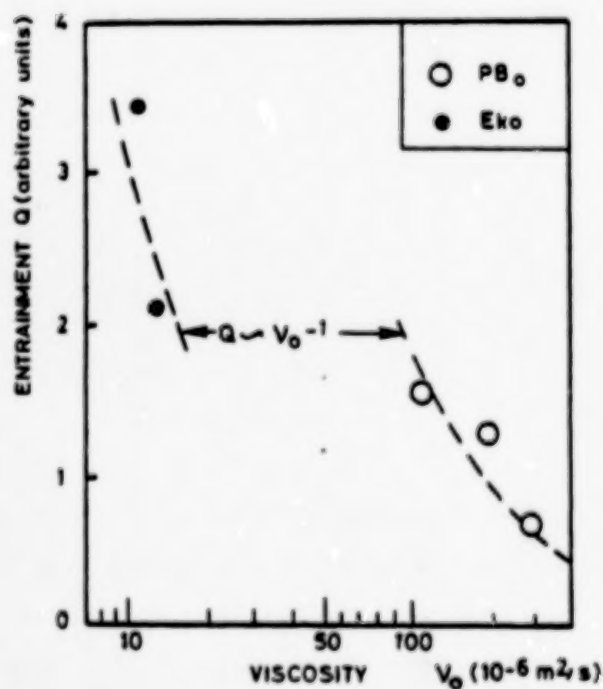


Figure 12 Entrainment measurements with different oil film thicknesses



a) Q versus temperature T



b) Q versus oil viscosity v_o .

Figure 13 Entrainment measurements with different temperatures and viscosities

c) Entrainment with different oil layer thicknesses.

Q versus h_o data are presented in Figure 12, and indicate that Q is independent of h_o . Moreover, $N(d_o)$ was independent of h_o within the applied range $h_o = 0.2$ to 1.2 mm, and the maximum droplet size observed (≈ 1000 μ m) can be considerably larger than the film thickness h_o .

Experiments on oil dispersion in breaking-wave flumes with different values of h_o were also performed by Bouwmeester and Wallace (1986) and Milgram et al. (1978). That the dispersed oil concentration is independent of the layer thickness was also found by Bouwmeester et al., and can be observed from the data measured by Milgram et al. although they did not draw this conclusion.

d) Entrainment with different temperatures.

Q versus T data from experiments with PB₀ and Ekofisk oil are given in Figure 13a. The data are transformed into a Q versus v_o diagram in Figure 13b, but, apparently, this diagram does not demonstrate a simple relationship between Q and v_o similar to the relationship $d_o \sim v_o^{0.34}$ (Equation 1) where the viscosity covers different oil types and different temperatures. Nevertheless, Equation (1) must be valid for the submerged PB₀ and Ekofisk oil parcels after the initial break-up of the coherent surface layer into submerged parcels. Considering the empirical observation of equal maximum droplet sizes d_{max} in all breaking wave experiments (except for differences that can be explained from different rise velocities due to different values of $\Delta\rho$), considering the validity of Equation (1), and the hypothetical case that the initial break-up of the coherent surface layers is equal in the different experiments, then the conclusion must be drawn that $Q \sim d_{50}^{-3}$ and, therefore, $Q \sim v_o^{-1}$. (The line of argument is described extensively by Delvigne et al. 1987). The conclusion is not in agreement with Figure 13b, probably because the break-up from coherent surface layers into submerged oil parcels due to breaking waves will depend also on the oil-water density difference $\Delta\rho$, the oil surface tension σ_o , and the oil-water interfacial tension σ_{ow} . These parameters may be rather different for

different types of oil, but hardly changes with varying temperatures, see Table 1. The data in Figure 13 are too few and probably too inaccurate to demonstrate results by themselves in a clear empirical Q versus T relationship, but the following argued relation is in reasonable agreement with the measurements:

$$Q \sim \nu_o^{-1}(T) \quad (7)$$

where the viscosity $\nu_o(T)$ varies only with temperature. The agreement between Equation (7) and the measured data is shown in Figure 13b.

4.4 Oil entrainment equations

The stability of the dispersed oil droplets depends on the following parameters:

- a) intrusion depth in the water mass due to the breaking wave z_1 ,
- b) vertical diffusion coefficient in the ambient water ϵ_z , and
- c) buoyancy of the oil droplets expressed by the rise velocity $W(d_o)$.

The measurements showed submerged oil consisting of droplets in a wide size range, including quickly resurfacing oil parcels immediately after the breaking wave. Therefore, an applicable entrainment description must include the entrainment rate of oil droplets per size class. Considering the empirical Equation (3) which deals with the relative number of dispersed oil droplets per size class, and that the mass of an oil droplet is proportional to d_o^3 , then the entrainment rate per size class can be given by:

$$Q(d_o) = C(o) D_{ba}^{0.57} d_o^{0.7} \Delta d \quad (8)$$

where: $Q(d_o)$ = entrained mass of oil droplets with droplet sizes in an interval Δd around d_o , e.g., the interval $d_o - \frac{1}{2}\Delta d$ to $d_o + \frac{1}{2}\Delta d$, per unit surface area and per breaking event,

D_{ba} = dissipated breaking wave energy per unit surface area,

$C(o)$ = proportionality constant.

Empirical values of $C(o)$ for various oil types are:

$$\begin{aligned} C(PB_0) &= 840 \text{ (+ 200)} \\ C(PB_{10}) &= 510 \text{ (+ 130)} \\ C(Ekofisk) &= 1800 \text{ (+ 450)} \end{aligned} \quad (9)$$

The values in Equation (9) are valid if $Q(d_o)$ is expressed in $\text{kg/m}^2\text{s}$, D_{ba} in J/m^2 , d_o and Δd in metre (m), and if the (small) interval is taken as $d_o - \frac{1}{2}\Delta d$ to $d_o + \frac{1}{2}\Delta d$.

The values of $C(o)$ in Equation (9) were derived from experiments performed at a water temperature of about 13°C . The influence of the temperature on Q , as far as could be derived from the experiments carried out in the range from 2°C to 15°C (see Figure 13), is expressed by Equation (7) using the viscosity ν_o as the characteristic parameter. Therefore:

$$C(o) = \nu_o^{-1}(T) \quad (10)$$

The oil entrainment Q and the droplet size distribution $N(d_o)$ due to breaking waves, appeared to be independent of the oil surface layer thickness h_o , within the applied range $h_o = 0.2$ to 1.2 mm. No empirical data are available for very thin oil surface films where the entrainment per breaking event Q is restricted to the volume of the surface slick. It is suggested that oil droplet dispersion is assumed to follow the empirical relationships developed, for the range from the smallest size class to the size at which Q equals the surface slick volume. In fact this principle can be applied for all film thicknesses, because for large thicknesses, the large droplets computed in this way resurface quickly.

For practical applications, however, the entrainment rate per unit area, Q_r ($\text{kg/m}^2\text{s}$), may be more suitable for describing the dispersion of oil on a sea surface. The entrainment rate $Q_r(d_o)$ can be described by:

$$Q_r(d_o) = C(o) D_{ba}^{0.57} S_{cov} F_{wc} d_o^{0.7} \Delta d \quad (11)$$

with

- $Q_r(d_o)$ = entrainment rate of oil droplets with droplet sizes in an interval Δd around d_o , per unit surface area ($\text{kg/m}^2\text{s}$),
- S_{cov} = fraction of sea surface covered by oil ($0 \leq S \leq 1$),
- F_{wc} = fraction of sea surface hit by breaking waves ("white-caps") per unit time (s^{-1}).

5. Discussion and Conclusions

In the process of dispersion of surface oil due to breaking waves, the entrainment Q (= dispersed oil mass per unit surface area per breaking event, in kg/m^2) depends strongly on the length of time after the passage of the breaking wave, due to the resurfacing of large droplets. The following description of the entrainment Q and the droplet size distribution $N_u(d_o)$ is adopted for calculations on oil dispersion:

- a) The distribution $N_u(d_o)$ is all the same within the intrusion depth z_1 for small droplet classes that are not (yet) disturbed by resurfacing of droplets. z_1 is given by Equation (5).
- b) The relative values of N_u in the $N_u(d_o)$ distribution of Item a above, is given by Equation (3). In principle, Equation (3) can be assumed to be valid up to "infinitely" large droplets, but the very large droplets resurface almost immediately.
- c) Absolute values of $N_u(d_o)$ in given circumstances are required for at least one small-droplet size class in order to perform dispersion calculations. Empirical data are presented in this study in terms of Equation (8) and the attendant entrainment coefficients $C(o)$ in Equation (9). The influence of temperature is given in Equation (10). The entrainment coefficients are independent of the oil surface layer thickness and the water salinity.
- d) The distribution $N_u(d_o)$ within z_1 can be made up according to sections a, b, and c from the smallest droplet size (in principle, $d_o = 0$) until the size where Q equals the mass per unit area of the original surface oil. Empirical evidence was obtained for cases with surface layer thicknesses in the tenths of millimetres and

millimetres range. It is suggested that one use this method for all layer thicknesses, including sheen of oil ($h_o = 10^{-4}$ mm). In the case of sheen, the model predicts the full and stable small droplet dispersion of surface oil hit by a breaking wave.

- e) The stability and vertical diffusion of small oil droplets and the resurfacing of large droplets in the residual turbulence conditions of the ambient flow after the breaking wave event can be calculated, starting from the conditions described in Items a,b,c and d above, with the diffusion equation:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial z} \left(c_z \frac{\partial c}{\partial z} \right) + W(d_o) \frac{\partial c}{\partial z} \quad (12)$$

where $c = c(d_o)$, oil concentration per droplet size class,
 c_z = vertical diffusion coefficient,
 $W(d_o)$ = terminal velocity of oil droplet with size d_o .

The empirical relationships and coefficients for the dispersion of oil due to breaking waves and/or turbulent seawater conditions can be applied in mathematical models where the hydrodynamical conditions of the sea are known. The hydrodynamical conditions must include the statistics on breaking waves on the sea surface (probability of breaking, breaking wave energy dissipation), and the diffusion characteristics in the water column; a literature study on these subjects was performed by Delvigne, Roelvink and Sweeney (1986).

Lack of empirical data and, therefore, suggestions for future research concern the following items:

- a) Dispersion (Q and $N_u(d_o)$) of thin oil sheen. In the case of a spill, extensive areas of the sea surface can be covered with oil sheen, some times due to resurfacing of oil droplets windwards of the massive oil slick. The suggestion in the previous section d should be checked.
- b) Dispersion of high-viscosity oil and emulsified oil. Fast emulsification of surface oil takes place in many field situations reducing considerably the dispersion of oil.

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